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NOTES

ON

IRRIGATION WORKS

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IRRIGATION WORKS

A COURSE OF LECTURES DELIVERED
AT OXFORD UNDER THE AUSPICES
OF THE COMMON UNIVERSITY FUND

BY

N. F. MACKENZIE

HONY. M.A. OXON.; M.INST.C.E.

(Lately Under Secretary for Irrigation to the Government of India)

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PREFACE

Under the auspices of the Common Fund of Oxford University, a course of lectures on Irrigation Works was delivered by the Author in the winter of 1909. The lectures were addressed to Students of Engineering and to Students of Geography; the former interested in the subject from the professional, and the latter from the economic point of view.

A few only of the many problems in engineering and in economics which have to be solved by the irrigation expert could be dealt with in the time available; and the following were selected as the subjects of the lectures :—

(1) Introductory, giving some general idea of irrigation works and their results.

(2) The statistics required for the preparation of an irrigation project.

(3) Types of weirs and the principles on which their design is based.

(4) The development of Egyptian irrigation since 1884.

(5) On the design of irrigation channels.

(6) Irrigation revenue and land revenue in India.

In his lectures the Author confines himself almost entirely to examples of irrigation works in India and in Egypt, as these countries contain, probably, the most interesting object lessons in modern scientific irrigation.

The Author has to express his indebtedness to various authorities for the information of which he has made use :—

To the Government of India, who permitted him to use their statistical and professional records, and to the Institution of Civil Engineers for the use of their Minutes of Proceedings.

To Sir William Garstin for information regarding the Nile; and to Sir John Ottley and Sir Thomas Higham, both formerly Inspectors General of Irrigation in India.

Mr. R. B. Buckley has permitted him to make use of his work on the "Irrigation Works in India"; and he is also greatly indebted to Sir Hanbury Brown, the author of "Irrigation as a Branch of Engineering," and to Sir Hanbury's publishers, Messrs. Constable & Company, for most of the information relating to Egypt.

In presenting his lectures in book form, the Author is aware that his treatment of the subject is necessarily curtailed and incomplete; but he hopes that their publication may lead some of his readers to study in detail a most important and specialised branch of Engineering Science.

N. F. M.

OXFORD, 1910.

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CHAPTER I

INTRODUCTORY

IRRIGATION, though agricultural in its object, has become a very special branch of engineering, owing to the nature of the works necessary for the proper control and distribution of water. Before proceeding to consider irrigation works from a technical point of view it will be of interest to review generally the local conditions which from very early times have led to the practice of irrigation, and this will involve discussion of the utility and value of irrigation under given conditions.

The practice of irrigation is of very great antiquity, and one of the earliest examples of irrigation works of which we have record is of interest as illustrating not only the prosperity which accompanies a well-managed irrigation system, but also the ruin and desolation which, in a country dependent on irrigation, inevitably follow neglect of the proper maintenance of its irrigation works. The country referred to is Mesopotamia, and particularly the alluvial plain in the south-east lying between the Euphrates and the Tigris, and which is known to us as Chaldea or Babylonia. Much of the history of Chaldea has been deciphered from local inscriptions, and not the least interesting are those relating to irrigation. These inscriptions fully bear out the statements of comparatively recent historians, of whom perhaps the most trustworthy is Herodotus. The whole of Chaldea is described by Herodotus as densely populated and thickly studded with great cities, and the cultivation

of the country was regulated by large canals, of which the three principal carried the waters of the Tigris towards the Euphrates above Babylon. Such was the fertility of the soil that grain yielded as a rule a two-hundred- and occasionally a three-hundred-fold return to the cultivator, and Pliny mentions that two crops of wheat could be reaped annually.

Chaldean chronology is somewhat obscure, but from an inscription of one of the Kings of Babylon, whose epoch is fairly well determined, we know that one, at least, of the great canals was in existence 2,200 years before Christ, and most of the Chaldean and later the Assyrian monarchs of Babylon appear to have devoted considerable attention to the maintenance and development of the canal system. As irrigation was the foundation of Babylonia's prosperity, so was the want of irrigation the chief cause of her decline. In the course of centuries the canal system of Babylonia suffered many vicissitudes; time and again the canals were ruined by floods or by neglect of the works, but it was not until the thirteenth and fourteenth centuries of our era that the irrigation system received its death-blow, during the troublous times of the invasions of the country by the Mongols and Tartars. With the destruction of the canals cultivation became impossible, and Babylonia rapidly sank into the state of barren desolation which it now presents.

This ancient irrigation system is interesting for reasons other than its antiquity. The flood season in the Euphrates and Tigris occurs six months later than in the Nile, and in consequence the flood system of irrigation as practised in Egypt becomes impossible, as the summer has already arrived before the waters recede, and though crops would germinate if sown, they could never arrive at maturity under a parching sun and in the absence of rainfall. There is good presumptive evidence therefore that the success of Chaldean irrigation must have been attained by what is known as perennial irrigation, a system which is usually supposed to be of very recent development.

From an engineering point of view what is termed by Sir William Willcocks the re-creation of Chaldea presents no insurmountable obstacle; and given the solution of political and financial difficulties, the time may shortly come when the restoration of the Chaldean system of irrigation works will effect for

Mesopotamia what the development of the Egyptian system has, under British engineers, accomplished on the Nile. At a recent mass meeting of the Jewish Territorial Organisation it was proposed that the colonisation of Mesopotamia should be undertaken by the Jews, and that contracts should be entered into with Turkey providing capital and population for the regeneration of Mesopotamia. Sir William Willcocks has reported that for an expenditure of seven-and-a-half millions sterling some 5,000 square miles of land could be brought under cultivation and made capable of producing an annual revenue of one million sterling or some 13½ per cent. on the capital outlay. The immediate effect of the realisation of this scheme, which has no engineering difficulties, would be to convert Mesopotamia from a desert into one of the granaries of the world.

Without going further into details of ancient works, it may be mentioned that the hieroglyphics of the Pharaohs of the Twelfth Dynasty show that irrigation was practised in Egypt about 2500 B.C., and, to take an example from the New World, there are in Colorado and Arizona the remains of irrigation works, as to the origin of which even local tradition gives no information.

Irrigation may be defined as the systematic application of water to land with the object of promoting present or prospective vegetation. Rainfall is the primary source from which irrigation is derived, and the surplus rainfall becomes available for artificial irrigation when it accumulates or flows, either on the surface or in the subsoil, at a level sufficiently high to admit of its being diverted or raised on to the land. In all cases, before this can be done, certain works of construction are necessary, and these are called "Irrigation Works." To quote the words of the Indian Irrigation Commission:—

> "The term 'irrigation works' thus includes works of many varieties and magnitudes, ranging from the rude contrivances which enable the cultivator, by swinging a basket, to raise water from a pond to the huge embankment of earth or masonry holding behind it a lake of many square miles in area; or from the small temporary well, a mere hole in the ground lined with brushwood, to the great canal which, carrying for some hundreds of miles a volume of water equal to that of a large-sized river, delivers it into a network of smaller channels for the irrigation of over a million of acres."

As an indication of the magnitude of some of the Indian

irrigation works, it may be mentioned that the Chenab Canal in the Punjab irrigates in the Rechna Doab 1,830,000 acres, nearly 3,000 square miles, and this is a canal which is not yet fully developed. This irrigated area must not be confounded with the area "commanded" by the canal. Fields cannot be cultivated year after year without a rest, and a certain proportion of the area "commanded" by irrigation remains fallow every year. The area commanded by the Chenab Canal, that is, the area to a certain proportion of which water is annually supplied, is two and a-half million acres, or about the size of Devon and Somerset combined. When the canal is fully developed the area commanded will be three and three-quarter million acres, which is about the area of Yorkshire. The Chenab Canal is capable of carrying a maximum discharge of 10,730 cusecs. ("Cusec" is the contraction used in India to denote a discharge of one cubic foot of water per second; it corresponds to the American expression "second-foot.") The average summer discharge of the Thames at Teddington is something over 700 cusecs, so that the Chenab Canal, when running full, is fifteen times the size of the Thames in summer. The capital cost of the canal is about two and a-quarter millions sterling, and the net revenue, after deducting working expenses, amounts to 14 per cent. on the capital outlay.

Water, when applied to land for the general purpose of increasing or improving cultivation, is utilised in special ways and at special seasons, according to the object in view, the particular crop to be reared, and the local conditions of soil, climate, and particularly rainfall. We shall now examine some of the conditions which render necessary the practice of irrigation.

The term "irrigation" is perhaps most commonly associated with the practice of watering crops in arid regions where rainfall is either non-existent or is too scanty for the requirements of agriculture. Mere quantity of rainfall, however, is but a minor factor in determining the utility of irrigation; what is of much more importance is the monthly incidence of rainfall throughout the year. For instance, the average rainfall of a large portion of England, omitting the mountains, is roughly about 30 to 35 inches per annum, and this is so distributed throughout the year that artificial irrigation is never resorted to on any large scale.

Contrast with this the case of the great irrigating districts of

the United Provinces in India, lying between the Ganges and the Jumna. The average annual rainfall is 32 inches, or very much the same as in England. Over 90 per cent. of this rainfall, however, falls during the monsoon, that is in July, August, and September. The remainder, except for an occasional thunder shower, falls in December and January. Out of a gross cultivable area of twelve and a-half million acres, some ten and a-quarter million acres are under cultivation, including land lying fallow. Owing to the unequal distribution of rainfall throughout the year, the area artifically irrigated amounts to five million acres annually. Allowing for land lying fallow, this means that three-quarters of the annual cultivation in this area is dependent on artificial irrigation. About half of this area is irrigated from Government canals, and the remainder from wells and tanks.

The cultivation of unirrigated wheat in the Ganges-Jumna Doab affords a typical example of the connection between the incidence of the rainfall and successful agriculture. In a year of favourable distribution the cycle of events is somewhat as follows:—Rainfall amounting to several inches falls in the second half of September, the land is ploughed and sown in late September and early October, and the ground retains moisture sufficient for the seed to germinate. As a rule there is light rainfall in early October, and from October 15 to December 15 there is no rain, but often very heavy dew. In the latter half of December what is known as the Christmas rain arrives, amounting to from half an inch to one and a-half inches. This establishes the crop, which is much improved by showers at the end of January, when the ear is being formed; the crop ripens in February and is cut in early March. In an unfavourable season the rains cease in the first half of September, late September and early October are hot and rainless, the ground dries up, and much of the seed fails to germinate. The Christmas rain arrives in January, and only a few scanty showers are received. The plant is stunted and feeble, the ear is imperfectly formed, much of the crop is withered by the sun, and a partial or total failure results. In such conditions the value of artificial irrigation is represented by the difference between prosperity and famine.

A second reason for resorting to artificial irrigation arises when the crop is of an aquatic or semi-aquatic nature; the

varieties of rice cultivation present the best-known examples of this class of irrigation.

The irrigation of large areas of rice is one of the most difficult problems which have to be solved by the canal administrator, as unless the crop receives water just at the critical period the outturn is greatly depreciated, and a very few days may make all the difference between a bumper and an average crop. Up to a certain point rice is grown in a swamp, and, so long as the plant is not actually submerged, it benefits from an unlimited supply of water. Just before the crop matures, all standing water is run off the rice fields, and the soil must remain damp but not actually under water. During this period of comparatively dry cultivation, which lasts about fourteen days, the crop must receive a full supply of water at least once. The dry period of rice cultivation in Bengal, for example, lasts from September 26 to October 10. If rain falls during this period, which is called the *hathia,* the rice will mature unaided by irrigation; but otherwise water must be artificially supplied.

The critical period of Bengal or Patna rice cultivation thus lasts for fourteen days only, and the success or failure of the crop is dependent on the incidence of rainfall during this short period. It will readily be seen that, in a dry season, the canals in rice districts, such as the Sone Canals in the Patna division of Bengal, are taxed to their utmost capacity, while in seasons more favourable to the cultivator there is no demand whatever for artificial irrigation.

The artificial irrigation of rice is of advantage from another point of view, in addition to its value in supplementing deficiency of the late rainfall. Opinion is unanimous that systematic artificial irrigation not only increases the outturn of the crop, but also improves its quality. Experiments on the Sone Canals in Bengal have demonstrated that the average value to the cultivator of an acre of rice grown under artificial irrigation is Rs. 36, while an acre of rice grown from rainfall is worth Rs. 24 only. The evidence of crop experiments in Chhattisgarh in the Central Provinces shows that irrigation increases the yield 75 per cent. in a normal year, and fourfold or more in a year of drought; while in the Wainganga district of the same province the yield from fields solely dependent on rainfall during the last famine

was 150 lbs. weight per acre, while the irrigated fields yielded returns of from 1,000 to 1,200 lbs. Again, irrigation renders it possible to grow the better kinds of rice which are transplanted and less fitted to withstand irregularities in rainfall, instead of the hardier but inferior varieties which are sown broadcast. Another important advantage is that a second crop can often be raised on irrigated lands, which could never be attempted in the absence of irrigation. From what has been said it will be seen that in rice cultivation irrigation is a necessity when the distribution of rainfall is unfavourable; and is highly beneficial even when the incidence of the rainfall is most favourable.

A third general reason for the practice of irrigation arises when lands are irrigated for the sake of the encouragement to early growth afforded by the warmth of the water as compared with the surrounding air, or for the sake of the dissolved plant food which the water contains.

These are the determining causes of much of the irrigation effected in this country. It is not resorted to because the soil is dry and hot, for it is carried out in the winter months of the year; it is not resorted to because the crop is of an essentially aquatic nature, for ordinary meadow grasses only are watered, but in order that plant growth may be stimulated and fed. The well-known water meadows of England afford an example of this system of irrigation, which was practised on the Wiltshire Avon as far back as the Roman occupation of Britain.

A fourth and most important reason for irrigation arises when the solid matter suspended in the water is valuable as a manure, or acts directly, by deposition, in raising the level of the land. The inundation or flood system of irrigation, as practised in Egypt, is an example which will be referred to later, and in detail.

In England this system of irrigation is practised mainly in Lincolnshire on the Trent near the Humber, and the value of the water lies in the quantity and also in the quality of the suspended matter. As most of the examples of irrigation systems will be taken from India or from Egypt, it may be of interest to explain briefly the "warping" system of irrigation as practised on the Trent.

Between Gainsborough and the Humber the banks of the

Trent have been for centuries so constructed as to protect the land behind them from encroachment of the tide. A considerable tract of country was thus rendered fit for cultivation. Within the last hundred years arrangements have been made by means of which the rich muddy water of the river is admitted to the land, and the resulting deposit of silt not only renovates the exhausted soil, but also effects a considerable raising of levels. Large masonry sluices are constructed in the embankments, and these are fitted with regulating gates, so that the tidal water is admitted or excluded at will. During spring tides usually, the water is admitted to the land, where it is ponded up by means of embankments previously prepared, and after depositing its silt it is permitted to return to the river on the falling tide. Considerable skill is exercised in controlling the water so as to obtain the kind of deposit most suitable for cultivation. When the water is first admitted, the heavy suspended matter, which is pure sand, is first deposited; the second deposit is a mixture of sand and mud which is exceedingly fertile and forms a valuable soil; lastly, the fine, light mud is deposited, which forms a soil, rich, but too tenacious to be of practical value. The object aimed at is to spread a layer of the second deposit evenly over the surface and to prevent the formation of the stiff clay deposit on the top. This is effected by keeping the water in constant circulation by manipulating sluices or valves constructed under the banks or "warps" which divide up the area under treatment. The light particles of clay are deposited in still water only, and the flow of the water is sufficient to prevent the deposit of the clay, while not so great as to interfere with the formation of the mixed deposit of clay and sand.

The formation of new soil is the principal object for which warping is employed, but the quantity of water may be regulated so as to give only a slight deposit to act as a manure, and this form of manuring is often resorted to for the improvement of arable land.

Warping operations usually occupy two years, one year for the formation of the silt deposit, and one year for drying and consolidation; the new soil becoming sufficiently consolidated to permit of cultivation during the third year.

In the foregoing remarks, the conditions under which irrigation

may be practised have been indicated on general lines; whether for increasing generally the produce of the land, or for securing crops against the effects of insufficient or unequally distributed rainfall; certain facts as to the utility of irrigation have been incidentally touched on; and there now remain two economic aspects from which irrigation works and their results may be considered.

There is first the purely commercial aspect, in which the chief point to consider is whether the work will return a sufficient percentage on the capital outlay. In India, works which are expected to fulfil this condition are classified as "Productive" works. The criterion is, briefly, that the works shall return, within ten years after completion, a net revenue sufficient to cover interest on their capital account. A time limit is fixed so that irrigation may be established and developed, and the capital account includes not only the cost of construction, but also any accumulation of interest which has not been cleared off.

The principal factors in determining whether the works will prove "productive" are the cost of construction, which is a matter of estimates; the cost of maintenance and working expenses, which may be arrived at from the experience gained on similar works in operation; and the gross revenue which may be expected in the form of water rates. This last item depends on the area to be irrigated, on the class of crops for which water will be required, and also on the increased value to the cultivator of his irrigated produce; or, briefly, it depends on the amount which the cultivator is willing to pay for his irrigation.

The second aspect from which irrigation works may be regarded is of great importance in countries like India which are subject to periodical famines. The point for consideration—to quote from the Report of the Indian Irrigation Commission—

"is not whether the works are likely to prove directly remunerative, but whether the net financial burden which they impose on the State in the form of interest and maintenance will be too high a price to pay for the protection against famine which they may be relied on to afford."

To put the point in other words, is it better, in the long run, to make up the annual deficit on a canal which does not pay its way, but yet protects a certain area from famine; or is it better to have no canal and pay a lump sum down for the relief of

famine when it actually occurs? The problem is obviously one which calls for very careful and detailed consideration. Such irrigation works, not directly remunerative, have, however, been constructed by the Indian Government, and they are classified as "Protective" works; the annual loss on them being, as it were, a premium paid for famine insurance.

The principal factor which goes to the solution of the problem of protective irrigation works is what has been termed "the protective value of an irrigated acre." Given the fact that famines have occurred in certain districts and at certain intervals, and given the amount expended in famine relief, we can say that, for any given district, famine relief has cost so much per annum. This annual expenditure capitalised may be taken as the limit of unproductive expenditure which may be incurred by the State now for the sake of avoiding the future cost of famine relief in that district. We must next consider the area which must be brought under irrigation in order to protect the district; this depends on the population, the habits of the people, and on the irrigation already existing. The capitalised cost of famine relief divided by the acreage which must be brought under irrigation is the direct protective value to the State of an irrigated acre. To this must be added the capitalised value of the net revenue per acre which may be expected to accrue to the State by the introduction of irrigation. If irrigation can be introduced at a less cost per acre than the amount thus arrived at, then the State can afford to construct a Protective irrigation work; otherwise it is cheaper for the State to pay a lump sum for the relief of famine when it occurs, rather than bear the annual burden of an unremunerative work.

The aspect of Protective irrigation which has just been indicated is purely financial; there is also the moral aspect to be considered. What amount is the State bound to expend, or justified in expending, in order to protect a district from the miseries of famine? But the answer to that question, though a potent factor in governing the famine policy of the State, is one which hardly comes within the province of the irrigation engineer.

It may be mentioned that the classification of irrigation works as Productive and Protective gives no real indication of their

financial success; the classification is based on the expectations formed of their financial results when their estimates were under consideration, and these expectations are not invariably realised. A good many Indian irrigation works, though classified as Productive, have failed to justify their classification; they nevertheless have their protective value. A notable instance of the opposite is the Swat River Canal in the Punjab, which, though classed as Protective, pays from 8 to 10 per cent. on its capital, and is therefore highly remunerative.[1]

In considering the general economic aspects of an irrigation work it is sometimes urged that the indirect benefits of irrigation are quite as important as the direct financial results themselves. There is undoubtedly a real, though intangible, indirect return to the State on successful irrigation works, but whether this indirect return is of sufficient importance to balance all financial considerations is at least open to argument.

The indirect advantages of irrigation are—

(1) The increase in the general prosperity and wealth of the community;

(2) The effect of irrigation and of water storage in increasing the humidity of the air and in raising the level of the subsoil water; and

(3) What has just been referred to—the prevention or mitigation of famine or scarcity.

The State no doubt shares in the general prosperity of the community in the form of increase in various kinds of revenue such as excise, income tax, stamp duties, etc., and, as in India, in the increased railway returns. To put an actual money value on these indirect receipts is practically impossible.

The second of these indirect advantages of irrigation is, however, of considerable importance to the engineer. Irrigation and large storage tanks have a considerable effect in increasing the humidity of the air and in raising the spring level in wells, thus rendering the subsoil water more available for irrigation. Also a certain amount of water evaporated will again be deposited as rainfall, and may render substantial assistance to irrigation; and the increased percolation into natural drainage

[1] This canal is now classified as "Productive."

outfalls may be picked up and utilised in areas far removed from the original source of supply.

It is, however, the reverse side of the picture that is important to the irrigation engineer. Irrigation, unless carried out on scientific principles, is apt to be overdone, and the effect of excessive irrigation may be to raise the level of the subsoil water so high that waterlogging and its attendant evils of agues, fevers, and impoverishment of the soil inevitably appear. Again, all natural waters contain a certain quantity of salts in solution. If the subsoil water channels are so overcharged that natural drainage becomes ineffective, water is continually drawn to the surface, evaporated, and leaves behind it an excess of saline matter in the soil. This saline efflorescence is a marked characteristic of districts artificially over-irrigated, and on some of the older canal systems in India has resulted in the deterioration of considerable areas formerly highly cultivated.

It is now fully recognised by irrigation engineers that the effective drainage of low-lying lands must go hand in hand with irrigation, and the evils indicated are never allowed to appear in a modern irrigation system. These evils were well marked in the system of drainless irrigation practised prior to 1883 in Egypt. The faulty alignment of the existing canals resulting in obstruction of the natural drainage outfalls and the use of natural drainages as irrigation channels were the principal causes of the evils; and in the delta the difficulty of leading surplus water away from the irrigated area was increased by the flatness of the country, much of which lies below sea level. Large areas had become waterlogged and unfit for cultivation, and it was soon recognised that an effective system of drainage was a pressing necessity. Many hundreds of miles of drainage channels have since been constructed, and in the year 1908 the expenditure on constructing new channels and maintaining those already existing amounted to £145,000.

As affording an illustration of several important principles in drainage operations, a portion of the Etah district of the United Provinces in India has been selected for description.

The district consists of an elevated alluvial plateau, the eastern slope of which dips suddenly down some 50 feet or more into the valley of the Ganges. Lying between the edge of the plateau

and the present bed of the Ganges is a belt of fertile land some one to three miles in width, in the centre of which a long line of swamps and hollows connected by a sluggish stream marks the ancient bed of the river. This valley is covered with a rich deposit of silt and is abundantly supplied with natural moisture.

The recent history of this fertile belt, which is called the valley of the Budhganga (literally, Ancient Ganges), is exceedingly instructive to the irrigation engineer. For some fifty or sixty miles a branch of the Lower Ganges Canal runs along the edge of the high land, roughly parallel to the Budhganga and never more than one or two miles away from it. This branch canal, which carries some 650 cusecs, is designed to irrigate the high land to the west, and the Budhganga valley was strictly debarred from any canal irrigation, as it was recognised that irrigation was not only unnecessary, but would even prove injurious. Prior to the opening of the canal in 1878 the level of the subsoil water in the valley was from 5 to 15 feet below the ground surface; rich crops of wheat, barley, millet, and even sugarcane were successfully reared, and the cultivators were the most prosperous in the whole district, though somewhat fever-stricken. The Budhganga was the natural drainage outlet of the valley, and the cultivators were quite alive to the importance of keeping it clear of weeds and other obstructions; in fact there was a recognised, though unwritten, law that each village kept clear the portion of channel within its own lands. 1878 was a famine year in the district, and famine was followed in 1879 by a terrible epidemic of fever, which swept away something like half the population. After this calamity, weed clearance was neglected on the Budhganga, as all the available labour was required for the fields; the spring level gradually rose, the volume of subsoil water being considerably augmented by percolation from the recently opened canal; and by 1886 cultivation had practically disappeared. In that and in the two following years the author visited the valley on many occasions, and it would be difficult to conceive a more apparently hopeless prospect. Subsoil water was level with the ground, all natural drainages were full of stagnant water and choked with weeds, the ground, even where comparatively dry, was tinged with green slime,

saline efflorescence was everywhere rampant, and a few scattered fields of miserable wheat were the only signs of cultivation. Fortunately, Government decided on the reclamation of the district, and as there was a lurking suspicion that the canal was at the bottom of the mischief, it was determined to place an irrigation officer on special duty to investigate the causes of the water-logging and to suggest remedial measures.

The story of the Budhganga drainage works is too long to recapitulate, but briefly the investigation proved conclusively that the primary cause of the trouble was the obstruction in the natural drainage outfall of the tract, and that, given a free outfall, there would be no difficulty in keeping the subsoil water at its original levels. The improvement of the main natural channel was put in hand at once, and consisted in weed clearance and in cutting across bends to shorten the tortuous channel and so improve the bed slope. Surveys and estimates for branch drains were put in hand and sanctioned, and by 1892 the valley was provided with a complete drainage system constructed and maintained by the Irrigation Department.

In 1900 the author was placed in charge of the district, and one of his first duties was to draw up from personal observation a report on the condition of the Budhganga drainage system. The difference in the appearance of the country since he last saw it, twelve years before, was a sufficient commentary on the efficiency of the drains. The whole valley where the soil was suitable was covered with cultivation, and the condition of the crops compared favourably with that of the canal-irrigated area on the uplands. Subsoil water level had sunk from 5 to 10 feet, saline efflorescence had practically disappeared, and the success of the drainage system lay patent before one.

In one particular instance the drains were too successful. A petition had been received by the civil authorities from certain cultivators praying for the reduction of the land revenue, on the ground that their crops had been destroyed. It was assumed, somewhat hastily, that the crops had been destroyed by flooding or by the rise in the subsoil water level; and the author was asked to investigate the complaint and advise whether any extension of the drainage system was required. The contention of the cultivators turned out to be not that their crops were ruined by

too much water, but that the action of Government in regard to the drainage had deprived them of the natural facilities for irrigation which they formerly possessed, and the contention was undoubtedly correct. Before the construction of the drains the subsoil water level was so near the surface that irrigation could be effected from shallow wells. After the drains were opened the water level fell so much that irrigation from wells necessitated the construction of deeper wells lined with masonry, for which they had neither the means nor the requisite skill. The restoration of the *status quo* was easily effected by abandoning the upper portion of the drain, which had never really been required.

The lessons to be learnt from the story of Budhganga are—

(1) That a rise in the subsoil water level, though often beneficial, is decidedly the reverse in low-lying areas;

(2) That the efficient maintenance of natural drainage outfalls should never be neglected; and

(3) That over-drainage may, in certain cases, be as prejudicial to cultivation as over-irrigation.

In the early part of this lecture some figures were given to indicate the magnitude of Indian irrigation works; these may now be supplemented by some figures as to drainage works. When the earlier canals were designed, the importance of drainage in conjunction with irrigation was not appreciated. The consequence has been that in the canal-irrigated districts of the United Provinces drainage works have been carried out subsequently to the establishment of canal irrigation. Since the older canals were opened, the introduction of irrigation has necessitated an expenditure of £300,000 on the construction of a system of drainage channels, the aggregate length of which is 3,300 miles, or more than one-third of the aggregate length of the earlier canals, together with their distributing channels. It may be added that the Irrigation Department of the United Provinces is responsible for the maintenance and working of, roughly, some 15,000 miles of irrigation and drainage channels. Statistics for the whole of India are incomplete, but there are some 45,000 miles of irrigation channels maintained by Government in India, exclusive of Burma, and, at a rough estimate, at least 100,000 miles of channel maintained by the cultivators.

This introductory lecture may be concluded by indicating very briefly the classes into which irrigation works may be divided.

The generally accepted classification is:—

(1) "Canals";

(2) "Tanks or Lakes"; and

(3) "Wells."

Under Canals may be placed all works for diverting the water of rivers and leading it on to the land.

Under Tanks may be placed all works for the storage of water and all natural depressions the water of which is used for irrigation.

Under Wells may be placed works for giving access to a subterranean supply or to the waters of rivers deep below the surface, and which must be raised vertically so as to flow on to the land.

The classification is convenient though somewhat indefinite. It is evident that in the case of a tank or storage work some form of canal is required for leading the stored water on to the land, and in fact the three classes of irrigation works indicated overlap each other to a considerable extent.

To these may be added a fourth class, viz., "Drainage Works," as in all modern irrigation systems irrigation and drainage go hand in hand.

CHAPTER II

STATISTICS REQUIRED FOR PREPARING AN IRRIGATION PROJECT

We now come to consider the preliminary investigations which must be undertaken before the project for an irrigation scheme can be weighed in the balance. In former days it was accepted as an axiom that the advantages of irrigation were sufficient to justify its introduction whenever financially practicable; its disadvantages under given conditions were not properly appreciated or were at any rate ignored. The result has been the expenditure of large sums of money on irrigation works of doubtful utility, or which in extreme cases may have proved actually injurious. In modern irrigation practice it is recognised that the complete preparation of preliminary statistics is the only sure basis on which to build an irrigation scheme, and much time and labour are spent on these preliminaries. For a recently proposed scheme in the Punjab the estimate for preliminary investigations amounted to £35,000, and this is money well spent.

The case of the Chenab Canal in the Punjab, which has already been mentioned, may be quoted as an instance of the kind of work involved in the establishment of a large irrigation scheme. The area commanded by this canal consisted of Crown waste lands, eminently suitable for canal irrigation, but quite uncultivated owing to the absence of water and of population, which consisted of a few scattered nomads.

Quite apart from the ordinary construction work, the manufacture of material, and the importation of labour, arrangements had to be made for supplying drinking water and supplies to the working parties, and in some instances these had to be carried many miles on camels. The colonisation of the land by introducing settlers from more congested districts was provided for. Arrangements had to be made for constructing a railway through the irrigated area for the exportation of surplus produce. Roads

had to be constructed, towns and villages had to be built, and, in fact, everything had to be done for converting a desert into a garden. In 1901 the canal irrigated some two million acres, and the population was 800,000 souls; a railway 200 miles long runs through the district, and is one of the best-paying branches of the North-Western Railway system of which it is a feeder. A headquarters town has been built with its municipal and canal offices, its club and its church, and villages for the cultivators are scattered over the irrigated area.

All this extraneous work had been foreseen and provided for, but it is evident that only a very detailed knowledge of the existing conditions of the country and a sort of prophetic vision of the conditions after the canal was made could have enabled the engineers to make arrangements for converting into a prosperous district what less than twenty years ago was literally a desert.

We must now consider these preliminary investigations more in detail.

The basis of all irrigation projects is a series of good maps of the country. Maps form the basis of all engineering projects, and it is necessary therefore to refer only to the particular details which differentiate an irrigation map from all other maps. First of all accurate levelling must be insisted on, and in a canal survey party both officers and subordinates must be expert levellers. In ordinary engineering surveys an error of 0·1 foot in a mile is generally accepted as good work. In canal surveys 0·01 of a foot per mile is a more exact measure of the degree of accuracy required. The reason is obvious; in dealing with surface slopes of a very few inches per mile, an error of a few inches may result in an attempt to make irrigation channels run up hill, whereas in railway work, for example, a similar error would necessitate but a slight alteration in gradient.

For irrigation projects the usual maps and scales in India are as follows:—

An index map of 1 inch to the mile without very much topographical detail, but showing all channels existing and proposed both for irrigation and drainage.

A general plan of 4 inches to the mile, showing channels, sites and names of masonry works, boundaries of villages, reduced

levels and contours, together with certain details of irrigation and drainage to be described presently.

A cadastral map to a scale of 16 inches to the mile, showing all field boundaries, and which is used in the field for sketching in the natural flow of surface drainage, the position of minor watersheds, varieties of soil, area of existing irrigation, etc., such detail being afterwards reduced from the 16-inch map and transferred to the 4-inch map. This 16-inch map is most useful in the field, as minor topographical details which would otherwise require very laborious surveys to locate them can be sketched on the spot with considerable rapidity.

There is very often a 4-inch map showing reduced levels and contours only, and in this case the ground levels on which the contours are based are omitted from the general 4-inch map.

Longitudinal sections may be 2 inches to the mile horizontal, and 2 to 5 feet to the inch vertical scale. These show ground levels, bed levels and gradients, water levels, positions of masonry works, and in fact all working details of channels, except the actual working plans of masonry works.

An irrigation map must be carefully contoured, and this in itself necessitates an immense amount of levelling, as the usual vertical intervals between the contours is 1 foot only. To those accustomed to work with the Ordnance Survey maps of England, for example, where the contours are spaced as a rule at 100 feet vertical interval, a map with 1 foot contour intervals comes as a novelty. It must be remembered that in irrigation maps one is dealing as a rule with very flat or gently undulating country, and differences of level which are hardly visible to the untrained eye are of great importance when lining out irrigation channels. The best method of locating contours for an irrigation map is to divide the country into squares of 330 or 500 feet side. The actual ground levels of the corners of the squares (spot levels) are determined by levelling, and the contours are interpolated on the map from the known levels of the corners of the squares. A map of this description is sufficient for lining out main and branch canals, but when it is required to lay out small channels for conveying water to each field or group of fields, something more detailed than even the contoured map is required, and the details demarcated on the 16-inch map are

used for lining out these field channels. In order that the water should command the country to be irrigated, all channels should follow the watersheds as far as possible, and no drainage should be crossed except when it is impossible to avoid doing so. Where drainage must be crossed, arrangements for passing the drainage across the irrigation channel must be provided; it is an axiom in irrigation work that drainage must never be obstructed. Small surface drainages may be diverted, and several of them may be combined into one defined channel, but the general principle is that the free flow of natural drainage must never be interfered with.

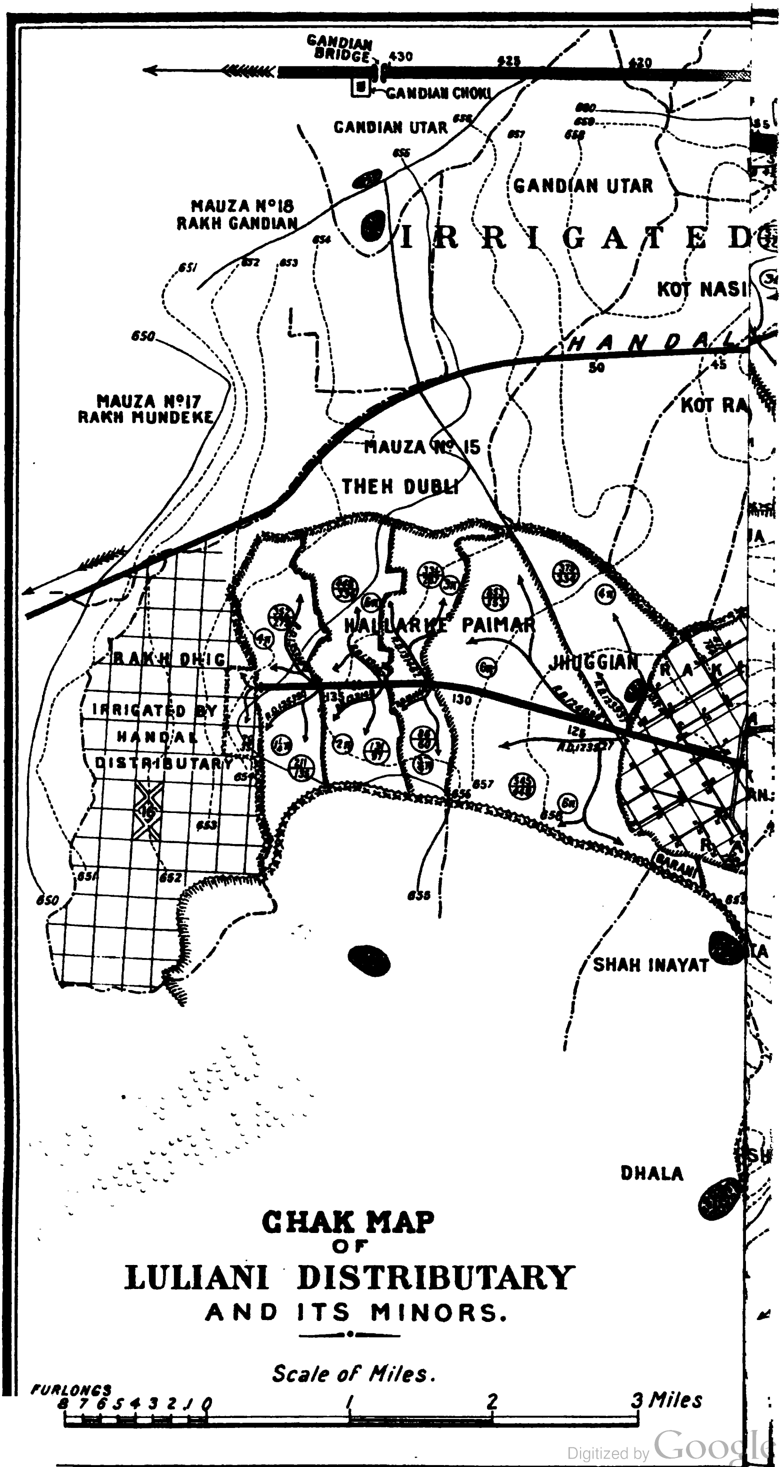
In Upper India maps of each village on the 16-inch scale (1/4,000) are published by the Cadastral Branch of the Survey Department, and these maps are also being prepared by the Egyptian Survey. Whenever procurable these maps should be used for field demarcation of the details now to be described. The maps show the boundary of each field, so that one's position on the map can readily be determined, and in addition each field is separately numbered. Even when such maps are not procurable, it is a simple matter to make a plane table sketch of each village boundary together with a few details of roads, and natural drainage channels, on which to base the work of demarcation. In an organised Cadastral Survey, in addition to the 16-inch map, there is a village record in which each field is entered by its number, corresponding to its number on the map, and this record, which is kept up year by year, contains much useful information. There is the field number, the owner's name, the cultivator's name, the area, kind of soil, whether cultivated in any particular season; if cultivated, the name of the crop and whether the crop was irrigated or unirrigated, and if irrigated, the source from which water was obtained, such as a canal, natural tank, or well.

The object of the demarcation on the 16-inch map is to show the following information :—

(1) The lines along which drainage flows off the fields and eventually finds its way into the natural drainage outfalls.

(2) The position of the minor watersheds separating these field drainages.

(3) The area and distribution of the principal soils.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MAUZA N°17
RAKH MUNDEKE
KOT RA
MAUZA N° 15
THEH DUBLI
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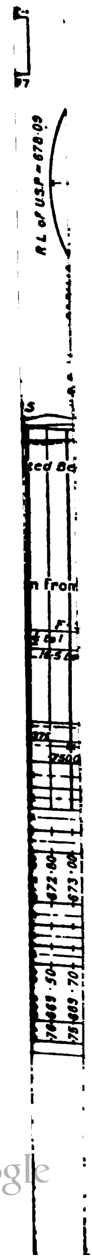
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(4) The area irrigated from wells or other sources, which does not require further irrigation.

Much of this work can be done in the office. From the village records the kind of soil can be shown on the map in distinctive colours, and the area usually irrigated from wells can be demarcated. When this office work has been completed, the 16-inch map is ready for use in the field. The surveyor then goes to a village, and by local inquiry finds out how the surface drainage flows off the fields near his own position, little by little he sketches on the map the flow of the surface drainage and the local ridges from which the waters divide, and he gradually sketches in the lines of surface drainage and the watersheds over the whole area of the village, and then proceeds to the next village. Local information gained on the spot from cultivators who have spent their lives in the same village is quite trustworthy, and the information regarding minor drainages and watersheds thus obtained is such that even a prohibitive amount of levelling would not give such accurate results.

This demarcation work may seem laborious and expensive, but in practice it is found that men of ordinary intelligence can readily be trained to demarcate several square miles in a day, and that without any previous knowledge of survey work; and experience has demonstrated that no practicable amount of levelling will locate the minor surface drainages and ridges so effectively as local inquiry on the ground.

Plate I. is a reproduction on a reduced scale of a 4-inch working plan of one of the distributaries of the Bari Doab Canal in the Punjab.[1] On the western portion of the map is shown the method adopted for dividing unoccupied land into square fields of 25 acres each, the watercourses being arranged to deliver water at the highest corner of the field. On the original plan the levels of the corners of the squares are noted; these levels have been omitted in the reproduction.

Plate II. is a working longitudinal section of the principal distributary of which Plate I. is the working plan.

Plate III. is a reproduction of a village map demarcated as

[1] The vernacular word "*chak*" in the map heading means "area" or "plot," and indicates that the area of irrigation allotted to each village or to each outlet is noted on the map.

described. It has been reduced from the 16-inch scale, and the numbers of the fields have been omitted to avoid confusion.

During the process of demarcating maps in the field, the clerical establishment is engaged in drawing up abstracts of soil areas, areas cultivable and uncultivable, areas irrigated and unirrigated; and in the case of uncultivated or uncultivable lands, the reasons for these lands being uncultivated, such as want of facilities for irrigation, swamps, sandy tracts, saline tracts, or want of agricultural population, are also noted. In districts where a Cadastral Survey has been carried out, most of this information is procurable from the Survey records, but some of it may have to be compiled in the field.

A very important class of inquiry in collecting irrigation statistics relates to the possibility of introducing higher-class crops than those usually cultivated, given an assured supply of water for irrigation. The difficulty in considering this problem lies in the number of factors, not unfrequently somewhat indeterminate, which have to be taken into consideration. Some of these factors may be briefly indicated by considering two examples of valuable crops.

Sugarcane.—The importance of sugarcane to India may be gathered from the fact that for the seven years ending 1902 the average world's outturn of cane sugar was seven and a-half million tons per annum; of this total, three and a-half million tons were produced in India. The world's outturn of beet sugar for the same period was five million tons annually, so that India's sugarcane produces 28 per cent. of the world's sugar supply.

Sugarcane is grown on well-drained alluvial loams and requires an assured supply of water practically all the year round. It also requires heavy manuring, which, in India, presupposes a community rich in cattle. Given a supply of cattle refuse, it is by no means certain that the cultivators can afford to use it for cane cultivation. Dried cattle refuse is a most important fuel in agricultural India, and if cattle refuse be used as a manure, it must be replaced as a fuel from some other source, such as waste jungle lands. The cultivation of sugarcane requires a certain amount of capital, not necessarily in the form of cash; and though it yields handsome profits, it is beyond the reach of a poor man.

Again the disposal of the crop is a matter of importance. The cane is grown in comparatively small patches and the cost of carriage precludes the establishment of a central crushing mill. Each village therefore provides its own crushing mills and boiling pans, and this again means capital expenditure. The question of markets is also important. In the villages, molasses and possibly unrefined sugar are manufactured, and there must be facilities for exporting the surplus produce. There is at least one canal in Upper India where a large area of sugarcane was anticipated by the engineers, but the cultivators refuse to grow it. Their sole reason is that there is no railway near at hand, and the cost of transport by road would swamp their profits.

The last factor to consider is the personality of the cultivator, whether he is industrious and enterprising and likely to avail himself of the improvements in agriculture, which he can effect by means of assured irrigation. As a rule the Indian peasant is quite alive to his own interests, but he is also intensely conservative, and he often hesitates to embark on the cultivation of a crop of which neither his forefathers nor himself have had practical experience. It may be mentioned incidentally that the introduction of sugarcane is important from the point of view of the canal administrator; the crop is so valuable that the cultivator can afford to pay a comparatively high water rate for his irrigation.

Another important and valuable crop is cotton, which is not only an important export from India, but cotton-spinning is also a flourishing internal industry.

Prior to 1860 the cotton exported from India was valued at three millions sterling per annum. During the American Civil War and immediately afterwards the cultivation increased by leaps and bounds until in 1866 the exported value reached the enormous total of thirty-seven millions sterling. Indian cotton, which has a short staple, cannot compete with the long staple American cotton in producing the finer yarns, and the present export value is about eight millions sterling. There are also about 200 spinning mills in India which employ some 170,000 operatives, in addition to innumerable hand looms which are found all over the country.

There are no statistics giving the outturn of the cotton-

producing countries, but taking the consumption of the spinning mills, it is said that India produces some 10 per cent. of the world's cotton supply.

Cotton is essentially a sun-loving plant, and its cultivation depends not so much on soil as on climate. It can be reared on sandy soils, loams, and on heavy clays, given a sufficiency of sun and of moisture, but excessive variation in the amount of moisture is injurious. A sandy soil does not retain moisture, a heavy clay retains too much, and the best soil for cotton is therefore a deep well-drained loam. Cotton requires a great deal of attention, and American statistics show that the cost of manual labour amounts to 54 per cent. of the total cost of growing the crop.

Given suitable soil, the personality of the cultivator is therefore perhaps the most important factor in considering the possibility of introducing cotton cultivation on a new canal, and this is due not only to the care which the plant requires, but also to the peculiar manner in which it suffers by over-irrigation. Cotton once established deteriorates by being irrigated, and only the most advanced cultivators realise this fact. In India there is a distinct inducement to the cultivator to over-irrigate the plant. Irrigation rates are levied on the crop, and if the cotton be irrigated up to the time it is gathered, the ground, after the cotton is gathered, retains sufficient moisture for a cold weather crop to be sown ; and given a slight rainfall, this second crop will come to maturity without artificial irrigation. The cultivator thus pays an irrigation rate for cotton only, but is able to raise two crops by paying one water rate. It is bad agriculture, for the excessive watering deteriorates the cotton, and the cultivator probably loses more than he gains. The deterioration of cotton due to over-irrigation has also been observed in Egypt. In 1903 the Assuan reservoir was filled and drawn on for the first time, and there was a great extension of the area under cotton in 1903 and 1904. Water was plentiful in those years, and yet the total yield of cotton was less than in 1901, when the area was less and when water was scarce. The official explanation was that water was plentiful and that the cultivators would not refrain from using it.

These two examples of sugarcane and cotton will serve to

illustrate the inquiries necessary for discussing the possibility of introducing higher-class crops, and they also to some extent explain the advantage of a fair working knowledge of agriculture to the engineer who makes irrigation his speciality.

Other statistics which have to be compiled refer to the number and classes of the population, and for these census reports must be studied, if available. This is important not only from the agricultural but also from the engineering point of view as regards the labour available in the district.

The labour market bears directly on the estimates, as if contractors have to import labour from a distance they must be paid higher rates than if labour were procurable on the spot. Knowledge of the habits of the people is also necessary; every agricultural labourer in India can do earthwork of a sort, and some are really expert. Some classes will follow the work wherever it goes, bringing their families with them; others will work only within a short distance of their village, returning to it at night. Some classes will work all day in wet foundations, while others will work in dry excavation only. These and many similar petty details become important when estimates amount to several millions sterling.

As an example of the distances from which labour has to be imported for canal works the case of the Nadrai aqueduct on the Lower Ganges Canal, which took four years to build, and which will be referred to presently in connection with rainfall, may be quoted.

The imported labour was:—

Carpenters and well sinkers from the Punjab	400	miles	distant.
Stonecutters from Allahabad .	300	"	"
Bricklayers from Bareilly . .	80	"	"
Lascars from Bombay . . .	800	"	"
Mechanics and foremen from large railway bridges	400	"	"

Ordinary labourers from a radius of 40 miles round.

When the work was in full swing some 10,000 men were employed on and round about the works, so that a large work practically sweeps the labour of the surrounding districts.

Means of transport must be noted, as it is often necessary to make temporary roads for carriage of materials, and if a railway runs through the district it often pays to concentrate operations for the manufacture of materials at large depôts close to the railway. In the case of the work just quoted a branch line of railway was run on to the work from an existing line five miles away, and it proved cheaper to rail coal 1,200 miles from the Bengal coalfields for engines and lime manufacture rather than cart wood from the nearest forest, with the additional advantage of the assured regularity of supply. This, of course, taking the comparative efficiency of wood and coal into account. A contract for fifty million bricks was given out before the railway was decided on, and the contractor had already entered into sub-contracts for wood fuel. Had he been able to use coal sent up by rail he would have made an additional profit of £3,000 on his contract. This affords an example of the necessity for entering into all possible details before work is begun.

In addition to noting the resources of the country as regards labour, it is very necessary to gain information as to the materials available. In addition to earthwork, canal engineering deals principally with bricks and mortar. There is no great expenditure on iron and steel, as in railways, and as the irrigation engineer is a pioneer, he is very often thrown on his own resources, and has not only to burn his own bricks and lime, but has also to teach his subordinates. This is an aspect of irrigation engineering which is hardly realised in countries where responsible and trustworthy contractors can be had for the asking.

We now come to perhaps the most important branch of the details comprised under "irrigation works statistics." That is rainfall statistics and the discharge of rivers and natural drainages.

It has already been shown how rainfall, and especially the monthly incidence of rainfall, has much to do with the necessity for irrigation and also with its utility. It is absolutely essential to have records of rainfall over the whole of the area in which irrigation is proposed, and it is equally essential to have details of the discharge of all channels carrying natural drainage

within that area, and also of the channel which is the source of supply. This implies that in the absence of definite rain gauge records one's calculations will be simply guesswork and of little value. In tropical countries rainfall records to be of any exact value must extend over thirty-five years, so as to include the cycle of cyclonic storms. This is also the period during which flood levels in rivers and other drainages should be observed. Records extending over this period are seldom obtainable, and one must be content with what one can get, but the important point to remember is that if the rainfall records are deficient, then a very large factor of safety must be allowed in designing the works. If accurate data are not available, much useful information as to flood levels can be gathered from old inhabitants, whose memory of facts is often very useful.

The important points connected with rainfall as far as irrigation is concerned are the quantity and monthly distribution of rainfall and the liability to failure or serious deficiency. Actual statistics of rainfall are best, but failing them, local tradition or information as to the crops which can usually be raised from rainfall only has a very considerable value. Where local tradition fails is in definite information as to the maximum discharge in drainage channels and rivers. This is quite explicable; a cultivator dependent on drainage for his primitive methods of irrigation remembers the years when the river failed him and he was hard put to it to find water for his crops, but he forgets in which of the many years when he had ample water the channel rose to the maximum level.

When a canal is to be taken out of a river, the important fact to determine is the minimum discharge which may be expected, for that determines the minimum supply available for irrigation. On the other hand, when a canal has to cross a river or other drainage channel, the important point is to know the maximum discharge, for on that is based the waterway to be given to cross drainage works. One of the first arrangements to be made in drawing up an irrigation project is to establish rain gauges all over the area under consideration and to establish river gauges on all rivers and drainage channels, and also to arrange for measurements of discharge, especially flood discharge, as often as possible.

The danger which may arise from designing cross drainage works on an underestimated flood discharge cannot be too strongly insisted on. The fate of the Nadrai aqueduct conveys such an impressive lesson to all engineers that its story may be told rather in detail, quoting from the official records written by officers on the spot. The Nadrai aqueduct carries the Lower Ganges Canal over the Kali Nadi, some 33 miles from Narora, where the headworks on the Ganges are situated. The Kali Nadi drains an area above the aqueduct of 2,377 square miles, the average annual rainfall being 32 inches on the catchment area. The canal itself discharges at the aqueduct 4,100 cusecs and is designed, in addition to its own irrigation, to supplement the supply in some branches of the older Ganges Canal. When the canal was first opened it supplied some 2,500 miles of canal and distributing channels, and while still undeveloped it irrigated 650,000 acres. These figures have latterly been much increased and are quoted as showing the importance of the canal at the time of the destruction of the aqueduct.

The aqueduct as originally designed was based on a flood discharge of 9½ cusecs per square mile of catchment, which corresponded to the then highest record flood of 23,000 cusecs. It consisted of five spans of 35 feet founded on wells sunk 25 feet below the bed of the river. It must be remembered that the discharge was no haphazard assumption, but was based on reliable rainfall and discharge statistics extending over nearly thirty years. The canal was opened in 1878, and on October 4, 1884, a flood calculated to be from 40,000 to 50,000 cusecs came down the Kali Nadi. This caused so much damage to the aqueduct that the necessity for a new work was immediately recognised. The old aqueduct was patched up, and designs and estimates for a new work of nine spans of 35 feet was drawn up and ready for sanction, when on July 17, 1885, a flood of 130,000 cusecs entirely swept away the old aqueduct and upset all former calculations. This extraordinary flood headed up 13 feet at the canal crossing, the depth above river-bed being 34 feet up stream and 21 feet down stream, which by no means represents the actual depth of water. It turned the left flank of the aqueduct, swept out a breach 300 feet wide in the canal embankment, and scoured out the bed of the river right down to the clay stratum

which is found at 30 feet below the river-bed. In addition to the aqueduct it swept away every bridge whether of road or railway on the lower 150 miles of its course, and the villagers, whom tradition teaches to build their houses high above dangerous flood level, escaped no better than the engineers, as many villages on the higher slopes of the valley were overwhelmed. The Kali Nadi fully justified its name—the river of the goddess of destruction.

Engineers find it difficult to digest the fact that a catchment of 2,377 square miles with an average rainfall of 32 inches did produce a flood of 130,000 cusecs, or 56 cusecs per square mile of catchment. Two experienced engineers, Mr. Garstin (now Sir William Garstin, of Egypt) and Mr. Good, who built the new aqueduct, happened to be on the spot during the whole of the flood and kept careful notes of levels and velocities, so that there is no doubt as to the discharge after allowing for unknown factors. The cause of the flood is contained in the Report of the Meteorological Department for July, 1885. After detailing the recorded rainfall it goes on to say:—

> "From the best information obtainable it seems that over 1,000 square miles of the drainage area of the Kali Nadi upwards of 20 inches of rain fell within a little more than twenty-four hours. Accurate statistics were not available over the whole area, as many gauges were found running over in the morning."

Where canal officers happened to be stationed they recognised that they were witnessing a record rainfall and took the precaution of emptying the gauges before they overflowed. This heavy rainfall accompanied a small cyclonic storm and was practically confined to the Kali Nadi catchment. The corresponding flood in the Ganges thirty miles away was 120,000 cusecs only, as against a maximum of nearly double that amount. There can be no doubt that in addition to the record rainfall the drainage system in the catchment area had a good deal to do with the excessive height and short duration of the flood; the whole thing was over in a day. The Ganges Canal, opened in 1854, irrigates a considerable portion of the Kali Nadi catchment area and was constructed before drainage principles were recognised. From 1875 onwards drainage operations were carried on with great vigour, channels were re-aligned, numerous drains were excavated,

and much was done to clear away every obstruction to natural drainage. Obviously an efficient drainage system carries off surplus rainfall much more quickly than would otherwise be the case, and results in increasing the intensity and diminishing the duration of floods. It is therefore necessary in designing cross drainage works to remember the possibility of maximum discharge being greatly increased by thorough drainage of the catchment area.

The new Nadrai aqueduct has fifteen spans of 60 feet as against five of 35 feet in the original. It is founded on 268 wells sunk 52 feet below the river bed. The waterway is 23,325 square feet, or 9·8 square feet per mile of catchment, and the mean velocity for an assumed maximum discharge of 140,000 cusecs is 6 feet per second. It may be mentioned that since the destructive flood of 1885 the maximum flood in the river up till 1902 was 15,000 cusecs.

Another point on which statistics are required is the level of subsoil water in the area under consideration. This can be noted during the progress of the survey preferably in wells in May and September for minimum and maximum heights in Upper India. In addition to the general well readings, lines of wells should be selected going right across the district; these are measured fortnightly throughout the year. Bench marks at known reduced levels are fixed on the wells, and from these the depths to water surface are measured and reduced to a common datum. These measurements give cross sections of subsoil water surface at different periods of the year. It is important to select wells which are not used for irrigation purposes, as the water level in such wells varies considerably if they have recently been drawn on. Wells used for drinking purposes only can generally be found, but if irrigation wells must be used, they should not be measured within twenty-four hours of being drawn on.

In the earlier canals of Upper India, such as the Eastern Jumna and Ganges Canals, little attention was paid to subsoil water level, waterlogging has followed the introduction of canal irrigation, and in a good many instances the restoration of the tract has been a source of considerable difficulty and expense. Drainage has done much, and in extreme cases it has been found necessary to prohibit irrigation from canals altogether

and advance money to enable the cultivators to dig wells or restore those which they had abandoned for the more easily obtained canal irrigation. In modern canal schemes areas watered from wells with a good supply, such as is indicated by high subsoil water level, are debarred from canal irrigation, which is right and proper, and quite a different procedure from first giving canal water and then being forced to prohibit its use. Subsoil water levels enable one to guard against mistakes of this sort, and also afford information as to the areas where the introduction of a canal and consequent increase of percolation may raise the level of the subsoil water to a dangerous extent.

A very good example of the use that records of subsoil water and well irrigation can be put to is afforded by the Sardah Canal project in Oudh, which has caused more discussion than any other scheme in India, and which the Irrigation Commission said was the most difficult problem they had laid before them. The first scheme was drawn up in 1870 to irrigate 3½ million acres in twelve districts in Oudh lying between the Sardah and the Ganges at a cost of six millions sterling. This was admitted by all concerned to be unnecessary, and since that date four separate schemes have been drawn up, the proposed irrigated area and the proposed expenditure being about the same in each, 600,000 or 700,000 acres at a cost of about three millions. The point for settlement was whether the height of subsoil water level and the area irrigated from wells and natural tanks did not render the introduction of a canal unnecessary. Opinion differed considerably according as the years were wet or dry, but the irrigation officers who in 1870 were keen to make the canal got more and more dubious as they got more and more information about the rise of subsoil water, and finally in 1899 they were generally opposed to its construction. The whole question hinged on the level of the subsoil water and on the area irrigated from wells, and but for the statistics of subsoil water which had been collected it is pretty certain that the canal officers would have pressed for carrying out a project which they have now abandoned, except for a very small canal to irrigate two unprotected districts which they have recommended should be thoroughly investigated afresh. After hearing all the evidence the Irrigation Commission declared

that they had not sufficient data to give a final opinion, and recommended a fresh investigation for a canal to irrigate six districts, and the words in which they point out the lines of the new investigation show the importance they attach to soil and drainage statistics :—

"The records show that along the alignment proposed for the main channels the depth to water level varies from a minimum of 11 feet in Hardoi to a maximum of 33 feet in Lucknow; and that in certain parts of some districts pure sand is found at a depth of 6 to 12 feet below the surface of the ground. But much more detailed information will be necessary before it can be said that the conditions with regard to water level and subsoil offer insuperable obstacles to the construction of a canal."

(The objection to fine sand near the surface is the enormous loss from percolation which would occur in the canals.)

"The areas must first be demarcated into which it seems desirable to carry canal water, having regard solely to their irrigational needs, the extent to which they must depend on canal water for their protection, and the suitability of their soils for canal irrigation. The subsoil water level within these areas, and outside them up to the limits of their main drainage outfalls, and the depth of overlying loam, must be observed and shown on a plan or cross sections of the country; and all matters bearing on the necessity for and the possibility of completely draining the tract likely to be influenced by the canal must be thoroughly investigated before any decision will be possible on this important question. The projects for the canal contain a good deal of general information on these points; but, though complete in engineering details, they were prepared at a time when the necessity for very detailed observations of the kind we have noticed had not yet been fully realised."

It will thus be seen that the decision as to the expenditure of several millions sterling depends on the questions of subsoil water levels and drainage referred to above.

The next point to consider in these preliminary investigations is what is called the "duty" of water.

The term "duty" of water or water "duty" is a term used by irrigation engineers to express the amount of work that water does or may be expected to do in irrigating crops. It depends, of course, on the kind of crop, and also on the position in a canal system at which the duty is estimated. For example, suppose that 50 per cent. of the water entering the head of a canal is lost by percolation, evaporation, and waste before it is delivered on to fields some hundreds of miles away—and this is by no

means an exaggeration; also suppose that one cusec of water flowing continuously will serve to bring to maturity 200 acres of wheat, then the duty of one cusec *at the field* is for wheat 200 acres. But in order to deliver that cusec on to the field two cusecs must be taken in at the canal head, so that for wheat the *canal head duty* of one cusec is 100 acres only. For rice the duty would be about one quarter of this. The volumes of water for which channels have to be designed depend on the class of crops to be irrigated, on their area, and on the duty for these crops. Duty is therefore an important factor in designing channels. In India the measure of duty is the area of a particular crop which one cusec flowing continuously during the life of the crop will bring to maturity. In America the measure of duty is the same as in India, using the expression second-foot instead of cusec.

Water duty is sometimes expressed differently in terms of the volume of water which will cover an acre to a depth of 1 foot, that is a volume of 43,560 cubic feet. This volume is called an acre-foot, and the duty is the number of acre-feet required to mature an acre of crop. In other words, it is the depth of the water expressed in feet (or in inches) which is applied to the crop. Wheat in India requires five waterings of about 4 inches depth each, or, say, a depth of 20 inches altogether. The duty for wheat is therefore 1·70 acre-feet or 20 acre-inches. In America water storage in a reservoir is designated as so many acre-feet, and this is useful, as the acre is the unit used for land areas, and the rainfall is expressed as so many inches in depth. The relation between the cusec or second-foot and the acre-foot is simple. A cusec running for twenty-four hours will cover an acre to a depth of 1·98 feet, or say 2 feet, so that one cusec running for twenty-four hours is equal to 2 acre-feet. Various other units are used in different countries, such as the cubic metre in Egypt and the litre in Southern Europe, instead of the cubic foot, but the principle is the same. Duty is, in short, any method of expressing the volume of water required to mature a certain area of a certain crop, whether that volume be expressed as the total depth of water applied to a unit area, or the continuous discharge required to mature a unit area. Incidentally, a somewhat curious discharge unit which is used in the Western

American States may be mentioned; it is called the miner's inch. Its amount is defined by State law, which differs in different States, and varies from 1/40 cusec in Arizona to 1/50 cusec in California. The expression often appears in American hydraulic statistics and is apt to puzzle the English reader. Briefly the definition is that the discharge through an orifice of so many square inches under a head of so many inches is equal to so many miner's inches.

The duty of water may be used in two ways. Given the supply available, the duty determines the area which it will irrigate; or given the area it is desired to irrigate, the duty determines the required discharge, the class of crop being assumed in both cases.

Water duty is obviously a matter of local conditions, such as soil, climate, rainfall, crop; all have to be considered; and when all is said and done there is a considerable element of uncertainty. It is, however, a very important factor in determining the dimensions of irrigation channels, and the difficulties must be faced. Experience gained on existing systems under similar conditions is the best guide; and in India, though the conditions affecting the duty vary so enormously in different districts, yet for each district there is a fairly well determined duty for each crop. For example, most engineers would accept 40 to 50 acres per cusec as a fair field duty for rice without further inquiry. When, however, there is little local information available, it is possible, by knowing how many waterings a crop requires to bring it to maturity and what depth of water is usually applied, to calculate a value for the duty.

Wheat in Upper India is on the ground for about four months, say 120 days, and receives five waterings of, say, 4 inches each. The earlier waterings are heavier than this, and the later waterings not so heavy, but 4 inches is a fair average.

Thus each acre of wheat receives $43{,}560 \times 1{\cdot}7 = 74{,}000$ cubic feet of water.

A cusec running continuously $= 86{,}400$ cubic feet per day, or 10,368,000 cubic feet in 120 days.

So that for wheat one cusec will irrigate $\dfrac{10{,}368{,}000}{74{,}000} = 140$ acres.

Now in the wheat area one can generally count on receiving

a certain quantity of rain in the wheat season, say 2 inches, or the equivalent of half of one watering, so that it may be assumed that 160 acres would be a fair duty for wheat.

In Upper India there are two crop seasons known as the Kharif and Rabi. Kharif crops or hot weather crops are maize, indigo, cotton, and millets. Also rice, which requires so much water that it is treated by itself, and sugarcane, which is irrigated in both seasons. Rabi crop is principally cereals.

The duties generally accepted are—

Rabi and sugarcane . .	110 to 140 acres per cusec.
Rice	40 to 50 ,, ,,
Kharif other than rice .	65 to 70 ,, ,,

It will be noticed that 160 acres is given above as the duty for wheat, which is the principal rabi crop. But it must be remembered that in the rabi the water must be given not only to wheat, but also to the area of sugarcane already standing, so that it will not go so far; and therefore the duty for rabi plus sugarcane is only 110 to 140 acres.

On all canal systems daily and monthly discharges are drawn up from the gauge records of every branch on the system, and from the irrigation records duties are calculated and published in statistical reports. These statistics convey no lesson to any one except the man who knows every detail of the conditions of the particular district to which they refer. In the hands of the local expert water duties afford most valuable information; they show whether water has been used economically or has been wasted, and he takes steps accordingly. But in the absence of local knowledge they may prove terribly misleading and worse than useless.

A simple example will illustrate this. Take the average duty of wheat as 150 acres.

A is a long distributing channel with scattered areas of wheat and great loss from percolation and evaporation. On such a channel 120 would be a good duty.

B is a short channel irrigating a compact area of wheat which can be reached without long channels. On such a channel 180 would be a good duty.

The returns show that the actual duty on A is 130 acres, while on B it is 160 acres. Without local knowledge one would say that B was doing much better than A, whereas the exact contrary is the case. A has been making the most of its water while B has been wasting it, and the local expert would make a note to investigate B and see where the wastage took place.

Being now in a position to determine the area which it will be possible to irrigate and what kind of crops will probably be irrigated at different seasons, the next thing to consider is what the proposed scheme will cost to construct, what it will cost to keep up, and what revenue it is likely to bring in.

As regards cost, it would obviously be a waste of labour to design and estimate the cost of the innumerable works on a great canal system, and then find out that the project was beyond the range of practical politics on the score of expense. It is necessary first of all to draw up a rough estimate without going into details, and then if the project seems likely to pay, it will be worth while going on to detailed consideration of cost. Or if it is fairly certain that the project will not be productive, it may still be worth considering from the protective point of view. The best way to arrive at a rough estimate of cost is to allow so much per acre on the area to be irrigated. The cost per acre naturally varies, but a good average figure can be got from comparison of the cost of canals already existing under similar conditions. It would serve no useful purpose to go into the causes of the variations in different provinces, but a few general figures may be of interest.

Take the Major Irrigation Works of India, that is, large works constructed by Government in the expectation that they would prove remunerative, either directly as Productive Works or indirectly as Protective Works. In 1901 there were thirty-nine such works in operation, the capital cost of which aggregated 366⅓ millions of rupees, or about twenty-five millions sterling at the present rate of exchange.

The area irrigated from these works in that year was over eleven million acres, so that the capital expenditure on Major Works for the whole of India was Rs. 33⅓ per acre.

The capital cost per acre by provinces was as follows:—

Sind	Rs.	18½	per acre	irrigated.
Bombay	,,	22	,,	,,
Punjab	,,	23	,,	,,
Madras	,,	24	,,	,,
United Provinces . .	,,	46	,,	,,
Bengal	,,	86	,,	,,

The conditions of irrigation works in Bengal are altogether exceptional, but it is useful to consider why Major Irrigation Works in the United Provinces should cost Rs. 46 per irrigated acre while in the adjoining province, the Punjab, the cost is exactly one-half. The cause of the difference lies principally in the incidence of rainfall in the two provinces. Rainfall in the United Provinces is greater than in the Punjab, the areas which require artificial irrigation are more scattered, and therefore require longer channels, and the heavier rainfall necessitates a greater expenditure on drainage works. Another reason is that the great Punjab canals were constructed as a rule at a later date than those of the United Provinces, and the Punjab engineers were thus able to avoid most of the costly mistakes made on the earlier canals.

Having arrived at a rough estimate of the cost of the project, the probable irrigation revenues must next be estimated. This is also a matter which must be based on the experience of similar canals. Irrigation revenue is the subject of a subsequent lecture, so the consideration of details may be postponed for the present. Water rates in India vary from R. 1 per acre for rice in Bengal to Rs. 50 per acre for sugarcane in Bombay; the average water rate for the whole of India is Rs. 3.5 per acre.

The final point for consideration is the cost of repairs and maintenance of the irrigation system; this cannot be actually foreseen, but it remains fairly constant, taking the average of a series of years. The average cost of maintenance for the whole of India is slightly over R. 1 per irrigated acre, and on Major Works it varies from R. 0.4 per acre in Sind to Rs. 2.5 per acre in Bombay.

This completes the statistics necessary for a rough estimate of financial results, and if the net revenue shows a fair percentage

on the capital cost, the project is ready for more detailed consideration.

The detailed examination of the project consists in running trial lines for the more important branches, designs for the larger masonry works are drawn up, such as head works, aqueducts and other large drainage crossings, and generally an estimate of cost is prepared more detailed than anything attempted in the preliminary investigations. Forecasts of financial results are drawn up, taking account of the time necessary to complete the work, which has a direct bearing on the interest accumulated during the time of construction, which will be added to the capital account. The project is subjected to expert criticism from the engineering, financial and economic points of view; and if it emerges satisfactorily from these tests, the estimates are submitted for sanction, and the project is placed on the list of works to be constructed when funds are available. In the meantime the engineers in charge of the work prepare working drawings, programmes of operations, and generally work out all details, so that they can begin construction as soon as funds are placed at their disposal.

In the foregoing remarks it has been taken for granted that, before preliminary investigation, the source from which the water supply is to be derived has been decided on. In the earlier irrigation schemes the boundaries of the area to be irrigated were limited to hydrographical boundaries, and the supply from each river was distributed to the area which could be commanded by its waters. Modern irrigation engineers in their search for sources of supply, have found it necessary to ignore these hydrographical boundaries, and the surplus water of one catchment is often diverted to supplement the deficient supply in another, and this diversion of supply has resulted in some of the boldest works of construction in modern engineering.

One of the most notable characteristics of modern irrigation projects is the width of view with which engineers regard sources of supply, and India affords some remarkable examples of the formidable natural obstacles which have to be overcome by the irrigation engineer.

In the extreme south of India the district of Madura has often suffered from famine owing to the uncertain nature of the rainfall

on the eastern side of the mountain range. On the western side of the range the rain never fails, and much of the drainage is carried by the Periyar River into the sea. A dam 155 feet high has been built across the valley of the Periyar, and the impounded waters are carried into the Vigai River on the east through a tunnel pierced under the rocky watershed. The tunnel, which is fitted with regulating sluices, is more than a mile in length, and a volume of 30,000 millions of cubic feet of water is annually diverted from the western to the eastern side of the peninsula.

Another bold project is now under construction in the Punjab. Three of the snow-fed rivers of the Punjab irrigate in their own particular areas; these are the Jhelum on the west, the Chenab in the middle, and the Ravi on the east. The existing irrigation takes up nearly the whole cold weather supply of the Chenab and Ravi, but there is water to spare in the Jhelum. The surplus water of the Jhelum is to be carried some 90 miles across country to supplement the existing irrigation, and finally drop into the Chenab just above the head of the existing Chenab Canal. From the Chenab a second canal is taken out to irrigate the upper portion of the Rechna doab lying between the Chenab and the Ravi. This Upper Chenab Canal passes across the Ravi, a river with a flood discharge of 200,000 cusecs; and carries its water into the arid districts of Montgomery and Multan. The head portion of the canal for 50 miles skirts the slopes of the Pabbi Hills, and encounters formidable hill torrents, discharging in flood volumes up to 156,000 cusecs. The estimated cost of the works is over five millions sterling, and an irrigated area of two million acres is anticipated.

The Sardah Canal project has already been referred to as illustrating the value of subsoil water statistics in determining the necessity for irrigation. For thirty years the Sardah supply has been regarded as ear-marked for the irrigation of Oudh, but the report of the Indian Irrigation Commission has practically decided that only a comparatively small canal is required. Surveys are now in progress for a canal to bring the surplus water of the Sardah 120 miles across country into the Ganges to extend the existing irrigation from the two Ganges Canals. Details are not yet available, as the Survey parties are still at

work, but the cost of the canal must amount to several millions, and the canal must cross the Ramgunga River, which, though practically dry in the winter, has a flood discharge of over 200,000 cusecs.

The projects quoted serve to illustrate the diversion of the surplus water of one catchment to supplement the deficient supply in another catchment; and also to illustrate the manner in which hydrographical boundaries are ignored by the irrigation engineer.

Intimately connected with the discharge of rivers is the relation between the rainfall on a catchment area and the run-off from the catchment. On this depends the question of the annual replenishment of a storage reservoir. The question is one of very great importance, and the factors which have to be taken into consideration are so complicated and vary so much in different areas that the engineer, even at the present day, has to depend very much on the exercise of his own judgment in arriving at the required data. The carrying out of a reliable systematic investigation into the relation between rainfall and run-off requires a large expenditure of money, and to be of any value, must extend over a long period of years. India and America have quite recently made hydrographical research of this nature the special care of their Geological Survey departments; Continental nations are also doing something; and in 1906 the British Association, in conjunction with the Royal Geographical Society, appointed a small Research Committee with the same object in view. Much has been done in different countries by individual engineers—Mr. Strange in Bombay, and the ate Dr. Deacon on the Severn, for example; but the field is very large, and the labourers are few.

The object of such an investigation is to ascertain:—

(*a*) The discharge of rivers in winter and summer, and the total annual discharge.

(*b*) The suspended and dissolved impurities in wet and dry periods, and the total amount carried in the year.

(*c*) The rainfall in different parts of each river basin.

(*d*) The area of each basin and the elevation of different parts of it.

(*e*) The area occupied by calcareous and non-calcareous

formations and by pervious and impervious formations—in fact, a geological survey of the catchment area.

A portion only of the rain which falls on a catchment flows off it. The rest is absorbed or evaporated. Absorption varies with the geological structure and surface configuration, and on the saturation or dryness of the soil, and on the presence of trees and vegetation in general. Evaporation varies with the temperature and the hygrometric condition of the air. The intensity of the rainfall has also much to do with the amount of run-off. The statistics relating to rainfall and run-off have been noted for many tanks in India, and these are very useful when the conditions of a new project coincide fairly well with those of an existing project. Failing such statistics, measurement of the rivers discharging from the catchment is the best guide to go by.

The following data extracted from Strange's book on Indian Storage Reservoirs are useful as approximations to what may be expected on an ordinary catchment area:—

Rainfall in twenty-four hours. Inches.	Condition of the Catchment Area and percentage of Run-off to Rainfall.		
	Dry.	Damp.	Wet.
0·25	Nil	Nil	12
0·50	Nil	10	14
1·00	5	14	20
2·00	10	25	34
3·00	20	40	55
4·00 and over	30—40	50—60	70—80

These figures show how the run-off varies with the saturation of the soil and with the intensity of the rainfall, but must be regarded as approximations only. They also do not cover the case of exceptional catchments like the rocky plateaux of Central India, from which it has been calculated that 98 per cent. of the rainfall is run off by the rivers.

It is of importance in designing storage works to know the maximum discharge or flood discharge which may be expected from a catchment, and also to know the rate of run-off or the time occupied in passing off the flood discharge. On these factors depend the discharge on which a waste weir is designed.

In tropical regions average rainfall is of no use in making allowance for maximum discharge, cyclonic storms accompanied by intense rainfall must be provided for, and the configuration of the catchment is important in such conditions. In steep rocky catchments the rate of run-off is much more rapid than in undulating well-wooded country, and from small areas the rate of run-off is relatively greater than from large areas.

The effect of cyclonic rainfall on the design of a storage reservoir is well illustrated in the case of the Marikanave storage in Mysore. The catchment area is 200 square miles and the annual rainfall averages 25 inches, which is calculated to give a run-off of 10,000 millions of cubic feet. The supply will, however, be subject to great fluctuations as the annual rainfall has been as low as 8 inches, and this, owing to a large number of existing tanks, gives practically no run-off into the large reservoir. It was originally proposed to construct a dam to store 20,000 millions of cubic feet. When the design came to be worked out, it was found from records of cyclonic rainfall that an escape channel for 60,000 cusecs must be constructed. This could only be provided by cutting a deep channel through hard rock, and as a matter of estimating it was found cheaper to increase the height and section of the dam so as to impound 38,000 millions of cubic feet and place the bed of the escape at a higher level, thus avoiding the expensive rock cutting.

The gross capacity of a reservoir is calculated from the areas bounded by the contours between high-water level and the bed of the reservoir. The available capacity is the volume stored between high-water level and the level of the outlet from the reservoir, which is governed by the level on to which the water has to be delivered. From this must be deducted the loss from evaporation which may vary from 3 to 10 feet in depth according to climate, and also the loss due to leakage and absorption, which depends on the nature of the bed and side slopes of the reservoir, but may roughly be taken as equal to half the loss from evaporation.

CHAPTER III

TYPES OF WEIRS

When irrigation is effected by means of a canal drawing its supply from a river, it is necessary to have some means of raising the low-water level in the river to a height sufficient to maintain the required supply in the canal. The method adopted is to build a barrier across the river, and such barriers are of various types, depending in a general way on the local conditions affecting the site selected, and the materials available for construction.

The Indian type of barrier consists of a solid submergible weir which affords no passage for the river until the water has risen sufficiently to pass over the top of the weir. The head sluices of the canal are placed immediately above the weir, and in order to clear away any silt deposits which may form in front of the canal head, powerful sluices are provided on the flank of the weir below the canal head. The Egyptian type is the "barrage," which is of French origin and consists of an insubmergible regulator formed of piers resting on a platform or floor, and carried well above flood level. Vertical grooves are cut in the piers and the level of the river above the barrage is regulated by raising or lowering shutters which slide in the grooves. In flood time the shutters are fully opened and the whole discharge passes through the vents with a minimum of obstruction.

The Indian weir and the Egyptian barrage are permanent structures, but there is in India a method of raising the water surface by temporary dams employed at the head of the great Ganges Canal, which is unique on a large scale, but which is also used on some of the Spanish rivers. At Hardwar, where the Ganges bursts through the Siwaliks, the river is confined in a comparatively narrow channel, and this is blocked during the period of low water by dams or bunds, which force the water

into the side channel from which the canal takes off. When the floods subside in September or October a bund composed of rough wooden crates or cribs filled with boulders is formed across the river. These rest on the bed, which is composed of boulders, and the cribs are weighted sufficiently to remain in position when lowered from barges. When in position the cribs are completely filled with boulders thrown in from the barges. There is a considerable amount of leakage through the first bund; and a second bund of small boulders and shingle is formed below it, and, if necessary, below that again a third bund of sand completely blocks the channel. When the river is completely blocked, provision is required for passing off any surplus water which may come down the river. A permanent escape head is therefore built quite separate from the bunds, down which excess water is passed by a channel which joins the river below. During the floods the bunds are swept away and are reconstructed next year. This system has been in use for over fifty years, and is adopted mainly for financial reasons. The bunds cost less than £2,500 per annum, which is very much less than the maintenance and interest on the cost of any permanent structure which could be built at the site. Hardwar is very favourably situated as regards the supply of materials for the bunds; there is an unlimited quantity of timber in the neighbouring forests, and boulders can be got for the cost of collecting them in the torrent beds.

Permanent weirs are generally designed to head up the low-water level from 10 to 13 feet, though the delta barrage on the Nile, with the help of a recently built subsidiary weir below it, now holds up 20 feet, each portion of the work holding up half the total head. In considering the design of a weir the effect of the afflux in causing possible inundation above the weir must be taken into account, and it may be necessary to construct marginal embankments to prevent water overflowing the adjoining lands. The weir therefore must not obstruct the flood waterway to such an extent as to raise the flood levels above it to an inconvenient height. There is also another effect of obstructing the flood-way which makes it desirable to limit the height of the weir. In several instances in India the afflux caused by the weir is so small as to be of no practical importance; but the obstruction to

the floodway results in irregular silting of the river bed above the weir, and the low-water channel after the floods may be right away on the opposite side of the river from the canal head so that it is difficult to get a supply into the canal. These difficulties do not occur in weirs or regulators of the barrage type, the obstruction offered by the piers is very slight and the shutters which hold up the water can be entirety removed in the flood season.

The earlier weirs in India were always built solid, but those of more recent design are a compromise between the immovable solid weir and the removable shutters of the barrage. The lower portion of the weir is built solid, and the crest is fitted with hinged shutters, which are raised when it is desired to hold up a low supply and are laid flat on the weir crest during the floods. These shutters are from 4 to 6 feet wide, and from 2 to 6 feet high. The falling shutters, in addition to reducing the obstruction in the flood-way, can be worked as scouring sluices, and their manipulation during the first rise of the floods is often a very important feature of river regulation.

Shoals are always formed in a river bed above a weir during the falling floods, and if allowed to remain may result in cross currents along the up-stream face of the weir during the next floods. Such cross currents should always be avoided as much as possible; as eddies, swirls and consequent scour in the neighbourhood of his works are the abomination of the canal engineer. The more evenly the floods pass over the weir, the better, and the less will be the cost of repairs after the floods are over. During low water the shutters are kept raised, and when the first floods come down the opportunity arises for clearing away shoals. A rise of several inches might be passed over the top of the shutters, but it is preferable to drop a certain number, selected so that the current passing over the lowered shutters impinges on the edge of a shoal and more or less rapidly cuts it away. When the scouring action ceases, the shutters are raised, and another set are worked in the same way, so that gradually much of the shoaling in the neighbourhood of the weir is removed.

Indian weirs may be classified as follows:—

1. Weirs with a vertical drop on to an impervious floor, such as the Narora weir on the Ganges.

2. Weirs without a vertical drop, but with an impervious floor sloping downward from the weir crest, such as the Khanki weir on the Chenab.

3. Weirs without vertical drop on impervious floor, consisting of a mass of stone with open joints sloping downwards from the weir crest, such as the Dehri weir on the Sone and the Okhla weir on the Jumna.

The Narora and Khanki weirs have been selected as types because both of them failed some years ago, and the reasons for their failure and the methods adopted in repairing them afford useful lessons in weir design.

The Narora weir was originally built as in the diagram (Plate IV. (*a*)), the 3-foot falling shutters being added a few years later to give additional command in the canal as irrigation developed. There are several dangers to which weirs are subject. There is first the danger of the overflow scouring out the down-stream bed and cutting backwards until finally the main work is undermined. The down-stream talus is designed to prevent scour, and as an additional protection at Narora the down-stream curtain wall was added. It is doubtful whether this curtain is of very much use; if scour ever was serious enough to work back to the curtain wall it is not likely to stop there. The talus must therefore consist of masses of stone sufficiently heavy to resist cutting back. There is always a certain amount of scour below a weir, but so long as it is kept well away from the work there is no danger. For example, some 250 feet below the Narora under sluices there is always a 30-foot hole. The talus, however, efficiently prevents cutting back and the hole is quite harmless.

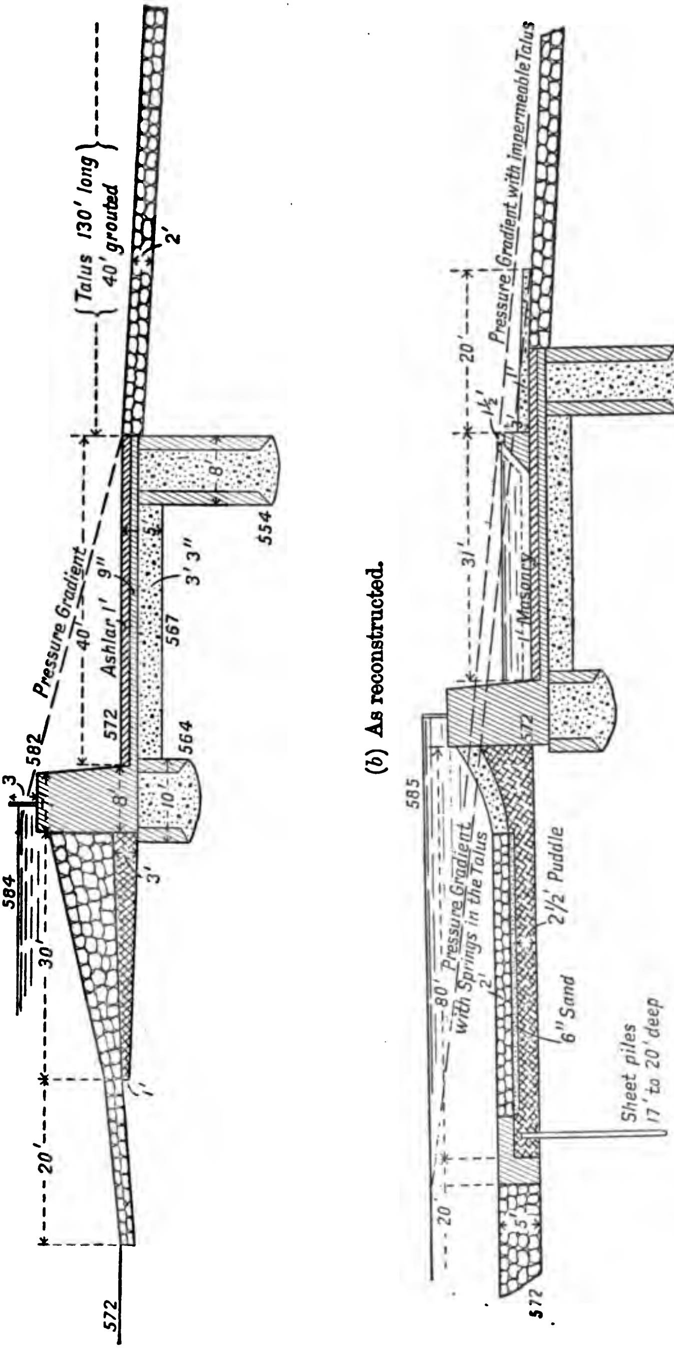
Another danger to which weirs are subject is leakage under the main wall or floor, which is known as "piping." There is generally water flowing underneath a weir, and if friction causes sufficient loss of head the velocity of the underneath water is so low that the foundation bed is not disturbed. If, however, water finds an open space underneath the weir in which the velocity is high enough to carry, with the water, grains of sand, then the pipe gets bigger and bigger, more and more sand is eroded and finally the weir is undermined.

It is important in designing a weir that the length of the

PLATE IV.—CROSS SECTIONS, NARORA WEIR ON GANGES RIVER.

(a) As originally built.

(b) As reconstructed.



enclosed space through which water has to flow to find an exit below the weir is such that the velocity due to the head is so reduced by friction as to be incapable of carrying sand along with the water. So long as springs run clear and carry no sand they are perfectly harmless. The danger of piping is increased by the formation of irregular shoals above the weir already referred to. These shoals tend to cause parallel currents along the up-stream face and so scour out the bed above the weir. At Narora and on other weirs this action is defeated by constructing long spurs of rubble at right angles to the weir so as to guide the flow at right angles to the weir crest. The Narora weir is 3,800 feet long and is divided up into sections by three such spurs, or dividing groynes as they are called. Before these groynes were constructed, parallel currents and scour near the weir wall were of common occurrence, but now the up-stream bed is an unbroken bank of sand and any scour up-stream is kept well away from the weir crest.

The dangers indicated above are more or less common to all weirs, but in addition the weir with a vertical drop, of which the Narora weir is an example, has two other forces to resist, viz., the pounding action of the water on the weir floor, and the force of the upward pressure, due to the head of water, which tends to blow up the floor. The first force is met by giving the floor a sufficient thickness and covering it with ashlar blocks. It is important that the ashlar should be properly bedded in mortar. Any imperfection in the joints is sure to lead to trouble, and it is a mistake in hydraulic works to have ashlar joints too fine. It is better to have thicker joints and be sure that they are properly filled with mortar.

The upward pressure on a weir floor due to the head of water held up is a very important factor in weir design and requires careful study. This upward pressure is diminished by the passage of the water through the foundation material on which the weir rests. The pressure is a maximum at the up-stream starting-point of the underneath flow, and is reduced at the point of exit to such an extent that the velocity is incapable of carrying sand with the water. To simplify matters we may take the pressure at the point of exit as zero. The pressure at any point can be found by drawing a right-angled triangle whose

base represents the length of the path of the water and a perpendicular to the end of the base represents the pressure due to head at the starting-point. The hydraulic gradient is then represented by the hypothenuse of the triangle, and the vertical height from the base to the hypothenuse represents the upward pressure at any intermediate point. It is well known from experiment that the line representing the actual hydraulic gradient is not in all cases a straight line—for gravel the gradient is steep to begin with and then flattens out; for clayey soil the gradient is flatter to begin with and then gets steeper. With ordinary river sand the normal slope is nearly a straight line, and we will assume that it was so at Narora, as any deviation would not affect the main argument.

At the point where the floor of the weir failed the upward pressure was between 10 and 11 feet of water, the water level above the weir being 12 feet above the floor; and to resist this upward pressure there was a floor 5 feet thick. The giving way of the floor is thus described:—

"At the time of the accident a strong spring burst through the floor at the toe of the crest wall, and passing under the stone flooring, lifted it bodily over a length of 340 feet to a maximum height of 2·23 feet. The weir wall settled in a length of 120 feet about 3 inches and the flooring showed vertical cracks. The grouted pitching below the floor was blown up. Up-stream of the part of the weir which was damaged the apron had disappeared and the wall was exposed to a depth of 8 or 9 feet. Borings through the floor revealed cavities extending to about 50 feet on each side of the point of fracture."

The interesting point is, what caused the accident? An eminent authority writes as follows:—

"The cause of the accident is clear enough. The upward pressure was too strong for the floor or the floor was too weak to resist the upward pressure."

But the local officers, who were men of experience and fully acquainted with the facts, decline to commit themselves to a positive opinion.

The author was in England when the accident occurred, but on his return he was called on to complete the repairs which had already been put in hand. He had opportunities of discussing the whole matter with engineers who had built the weir and some of whom were present at the time of the accident; and

one or two facts may be noted which make the cause of the accident doubtful.

The weir was completed in 1877, and the falling shutters were added in 1882; the accident occurred in 1898. Since the shutters were added the water was headed up, year after year, to 13 feet above the floor, which withstood the pressure without the slightest sign of a crack for sixteen years. Why did it suddenly fail when the head of water was 1 foot less than usual?

The second point is, why did the grouted pitching blow up? The upward pressure below it was very small, on the supposition that the sand foundation was intact and quite insufficient to blow up blocks weighing, as they did, half a ton and over.

The third fact is very significant. On the morning of the accident, springs in the talus were observed to be blowing sand, although up to that time they were running clear. The accident occurred a very few hours after this was observed.

The author's opinion, which he gives with all reserve, is that the floor was first undermined by piping: the concrete, or perhaps the concrete and masonry, settled away from the ashlar, leaving a horizontal joint into which water found its way, and this probably occurred when the water up stream and down stream of the weir was at about the same level. To resist the head of 11 feet when the water was ponded up there was only 1 foot of ashlar floor left, and it accordingly blew up. The talus stones were also undermined and shaken, and were then ripped up by the rush of water through the rent in the floor and were not blown up by hydrostatic pressure. When the floor first settled it would probably crack at the toe of the crest wall, thus accounting for the strong spring at that point. The sand-blowing in the talus is also accounted for by piping, as the removal of most of the foundation sand under the floor means that there was little friction to reduce the velocity due to the head.

It will be seen that the theory of piping and settlement is quite as consistent with the facts as the blowing up theory, and for this reason the local engineers are by no means positive as to the actual cause of the accident.

Let us now see how the weir was strengthened after the accident and the theoretical principles which led up to the means employed for strengthening the work.

There are two possible methods of strengthening the weir, either to make the floor strong enough to resist any possible upward pressure or to reduce the pressure under the floor. In the sound portion of the weir the latter was the remedy adopted, and the damaged portion was further strengthened by the addition of 18 inches of masonry. A dwarf wall 3 feet high was built near the down-stream edge of the floor to form a water cushion below the weir wall, and this has also the effect when the down-stream river bed is dry of counterbalancing 3 feet of the upward pressure. The reduction of pressure under the floor was effected by adding an apron of 2½ feet of puddle, extending 80 feet up stream and protected from scour by 2 feet of pitching above it and by a terminal cross wall of masonry and a mass of rubble. At the up-stream edge of the puddle a curtain wall of sheet piling was driven to a minimum depth of 17 feet and extended right across the river. The diagram (Plate IV. (*b*)) shows the weir as finally strengthened.

Before the accident the original puddle apron up stream had been scoured out by parallel currents and had been replaced by rubble pitching, so that the starting-point of underneath flow was against the weir wall itself. The new puddle apron threw the starting-point of the underneath flow 80 feet up stream, with the result that the pressure gradient was flattened and the upward pressure on the floor considerably reduced. The curtain of sheet piling lengthens the path along which the underneath water has to travel to reach its exit and still further reduces the upward pressure on the floor.

Neglecting the effect of the curtains, the diagram shows how the flattening of the pressure gradient lessens the upward pressure on the floor. It is assumed that the grouted pitching is not an integral part of the floor, and that the point of exit is at the end of the masonry. This is in accordance with the facts. At the same time, it is well to observe how a grouted talus, so constructed as to form an extension of the weir floor, has the effect of increasing the upward pressure on the floor, although it flattens the hydraulic gradient by moving the point of exit down stream.

There are certain conclusions to be drawn from the history of the Narora weir which are worth noting:—

1. The extension of an impermeable apron up stream decreases the upward pressure on the floor below the drop wall by flattening the hydraulic gradient; while the extension of an impermeable floor down stream, though it also flattens the gradient, increases the pressure on the floor.

2. A curtain wall is effective in reducing the upward pressure of the underneath water only if placed up stream of the floor. As regards upward pressure on the floor, it has no effect in reducing it if placed down stream, and is only a precaution against cutting back and undermining.

3. The water-tight floor below the drop wall should be strong enough and wide enough to withstand the impact of the falling water. It should also be strong enough to resist the upward pressure of the water at any point, and should be wide enough to obviate any blowing of sand at the point of exit.

4. Grouted pitching down stream should not be made an integral part of the floor, or, if it is, the effect in increasing the upward pressure on the floor must be taken into consideration.

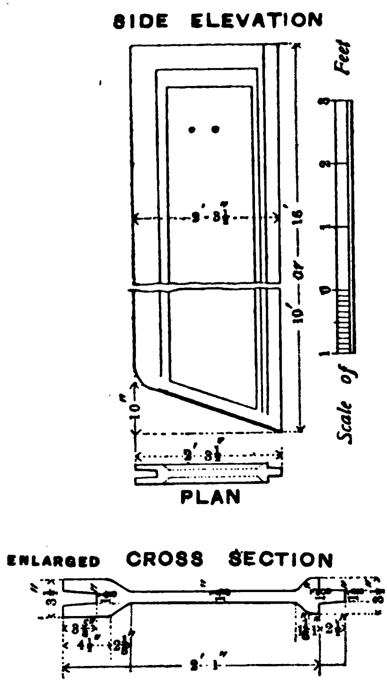
There are two points connected with the repairs of this weir regarding which a note of warning must be sounded. Up-stream curtains, whether of wells or piles, are more effective in preventing piping than a corresponding length of horizontal apron, as they alter the direction of flow and check the movement of sand; but this is true only if they form a perfectly water-tight curtain. Any intervals left in the vertical curtain form runs through which springs find a way, and unless the curtain is perfectly staunch it is more likely to assist piping than to prevent it. In the restoration of the Delta barrage on the Nile the greatest source of trouble was the leakage between the piles within which the original floor had been built. This difficulty led to the adoption of a special form of cast-iron pile (Fig. 1) in the Assiut barrage curtain. One side of the pile was grooved 3⅝ inches deep, and the other had a projecting tongue 2½ inches long. This tongue fits into the groove of the pile next it, and when driven there remains a space between the point of the tongue and the back of the groove. This space is first washed out by a water jet and is then filled with Portland cement grout, thus forming a water-tight joint. The Narora piles were of timber cut to a feather edge on one side, which

fitted into a corresponding groove in the next pile; and, judging from the difficulty experienced in getting the closing pile of a section driven into position, it is hoped that they form a water-tight curtain, though there is no proof that such is the case.

The second point is with respect to the up-stream puddle apron. The whole efficiency of the apron in moving up stream the point where underneath flow begins depends on there being a water-tight junction between the puddle and the masonry at the crest wall. This is undoubtedly a danger point. If, as may well happen, any portion of the bed up stream is laid dry, the puddle may shrink and thus lead to the opening up of a dangerous fissure; and in that case the point of underneath flow is not at the up-stream edge of the puddle, but at the crest of the weir wall. At Narora the puddle at the weir crest was covered with a concrete platform to prevent the puddle from erosion, and a tight joint is maintained between the concrete and the weir wall. This danger point, however, is worth remembering.

FIG. 1.

CAST IRON PILES



The repairs to the Narora weir have been described in detail as they exemplify the principles on which the design of recently constructed weirs has been based.

The Chenab weir (Plate V.) has been selected as an example of the second type of weir—without a drop, but with a sloping impervious floor down stream. Its history is also interesting, as in its original form it failed in 1895. As originally built, it

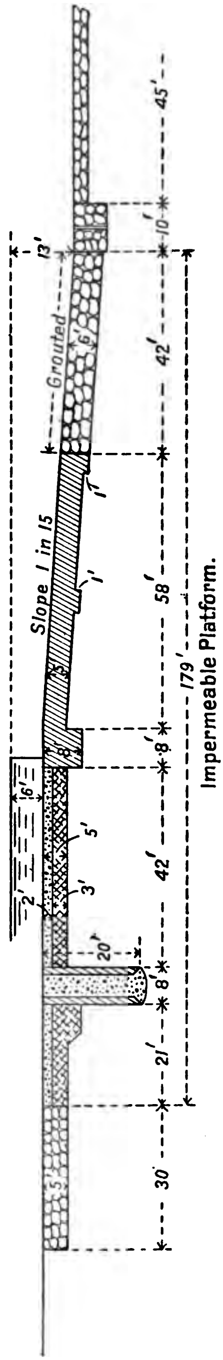


PLATE V.—CROSS SECTION KHANKI WEIR ON CHENAB RIVER.

consisted of a solid crest wall 8 feet thick and 8 feet high. From the weir crest a solid masonry wall 5 feet thick sloped downward at one in fifteen for 58 feet horizontal, and in continuation there was a grouted talus extending for 42 feet at the same slope as the masonry floor; this talus was 6 feet thick, and was terminated by a wall 10 feet wide, composed of blocks of masonry built in 5-foot cubes. Up stream of the weir wall was a triangle of stone pitching with a horizontal base of 24 feet, which was meant simply to prevent scour. The weir crest was fitted with falling shutters 6 feet high, and the up-stream water-level was 13 feet above the point of exit. In this case the failure was due to piping or leakage under the floor, which apparently took place along the line of an old side channel of the river which had been silted up. The impermeable base width of the weir in its original form was 108 feet.

The strengthening of the weir consisted, as at Narora, of the addition of a puddle apron 3 feet thick, covered by 2 feet of concrete, the apron extending 71 feet up stream of the weir crest. At 50 feet up stream of the crest a line of wells 20 feet deep forms a curtain wall, but it is doubtful whether these might not have been better omitted. Unless the wells are sunk perfectly vertical it is difficult to staunch the spaces between them by any method of piling. Up stream of the puddle there is a belt of pitching 20 feet wide and 5 feet thick for preventing scour. The impermeable base of the weir has thus been increased from 108 feet to 179 feet, the head of water remaining 13 feet, as before, but the point at which the underflow begins has been removed 71 feet up stream. The remarks on the Narora weir apron apply equally to the Chenab weir, as the principle on which the strengthening was based is the same in each, though the construction details are slightly different.

From what has already been said it will be seen that the length of impermeable floor is an important factor in designing a weir of one of the first two types, and the lengths adopted in several important works may be noted.

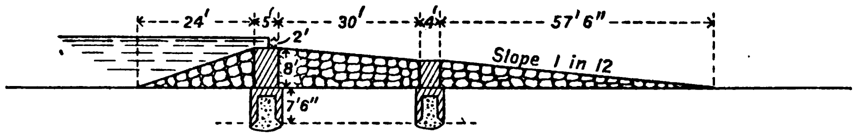
At Narora, before the accident, the floor length was 78 feet, with a head of 13 feet, or a ratio of six to one, and this, according to more recent ideas, was insufficient. After the restoration the floor length was 142 feet, with the same head of 13 feet, or a

ratio of fourteen to one, taking into account that 3 feet of head is neutralised by the cushion of water 3 feet deep which is maintained below the weir. At Khanki the original floor was 108 feet and the head 13 feet, a ratio of eight to one; after the restoration the floor length was 178 feet, with the same 13 feet head, or a ratio of fourteen to one. The remodelled Delta barrage in Egypt has 238 feet of floor and 14 feet head, or a ratio of seventeen to one; but owing to the inferior workmanship of the original structure the head has been reduced by the construction of a subsidiary weir below the barrage. On the Zifta barrage, one of the most recently constructed, the floor is 153 feet and the head 13 feet, giving a ratio of twelve to one.

The general conclusion is, therefore, that for rivers with sandy beds the ratio of floor length to head should be about fifteen to one, or, as a minimum, twelve to one.

The third class of weir consists of a triangular mass of rubble

FIG. 2.—CROSS SECTION DEHRI WEIR ON SONE RIVER.



laid on the river bed and divided by two, or sometimes three, solid masonry walls generally founded on wells sunk in the river bed. Such weirs are quite permeable, and their stability depends on their mass. The upper surface consists of a carefully packed layer of large stones on end. The diagram (Fig. 2) of the Sone weir sufficiently explains the construction of this type. This weir has falling shutters 2 feet high on the crest wall; the total head is 10 feet, which is equally divided between the two walls. The type is a permanent modification of the crib and boulders temporary bunds at Hardwar, already described.

The Okhla weir, on the Jumna, is a unique example of this type. It supplies the Agra Canal. It is remarkable for having no foundations whatever below the bed of the river. There are three cross walls built on the river bed, and the spaces between them are filled with rubble in the usual way. The total head is 13 feet, of which the down-stream wall takes 4 feet 9 inches, the

middle wall 4 feet 3 inches, and the crest wall takes 4 feet. Both the Sone and the Okhla weirs were situated close to extensive stone quarries, and the type adopted is one which gives very little trouble, given an unlimited supply of rubble. There is no question of puddle aprons or impervious floors; repairs are very simple, and, once the weir has arrived at a state of permanent régime, by filling up scour holes below it so as to prevent cutting back, the type is a very comfortable one to be in charge of. The adoption of this type depends principally on the cost of delivering stone at the site of the works.

The selection of the site for a weir has much to do with weir design. The point selected must be such that the canal will be able as soon as possible to deliver its water on to the fields by gravitation, without any necessity for lifting the water, and the shorter the distance in which this can be attained the better. But the point from which this command can best be attained is not necessarily the best site for the weir. The material of which the river bed is composed, the cross section of the river, the direction of flow above and below the weir, the nature of the river banks, have all to be taken into consideration.

A concrete example—that of the Narora weir—will best explain why a certain site was selected. The Lower Ganges Canal, which is supplied from the Narora weir, takes out on the right bank of the Ganges. For some 50 or 60 miles up stream of Narora the right bank of the river is a perpendicular bluff from 30 to 50 feet high. A canal taking out anywhere along that bluff would have to run in deep cutting for many miles before it reached the ground level. At Narora the bluff on the right bank suddenly leaves the river and runs away inland. Narora is therefore the first point at which the banks are favourable. The river at that point is not quite straight, but flows in a gentle curve; 4 miles up stream it is spanned by a railway bridge, and is trained to flow through the bridge at right angles. It then takes a straight course on to Narora, and below it curves gently away to the left. The flow of the river is therefore favourable. At Narora the section is fairly level, the bed is pure sand, and homogeneous sand is one of the best possible foundations to deal with. The flood width is not excessive—about 4,000 feet—and for all these reasons Narora was selected as the site for the weir.

The site has its disadvantages. The canal has to run for 20 miles parallel to the river before a suitable point can be found to pierce the high ground and find a way into the irrigation area. For 20 miles, therefore, the canal runs through the low ground near the river, and is never more than one or one and a half miles away from it. In an alluvial plain the river may suddenly change its course, and it must be kept away from the canal at all costs. This necessitates an extensive system of river-training works which controls the Ganges for 20 miles of its course, and is the most extensive river-training system in India. In addition, a spur of the high ground runs down to the river some 10 miles from the canal head. This has to be cut through, in a cutting some 80 feet deep and $1\frac{1}{2}$ miles long. Notwithstanding these disadvantages, the Narora site was selected, as any other site would have involved either the loss of command or a cutting some 50 miles long and from 30 to 50 feet deep.

Another important point to be considered is the width of the weir. One of the most unfavourable conditions in controlling a river is the formation of *irregular* silt deposits; and irregular silting may be minimised by a judicious selection of the weir site. The weir must extend from bank to bank, and, if possible, a straight reach of the river should be selected. Other conditions being equal, a site where the river is narrower than the normal width should be selected. The increased velocity over a short weir will necessitate heavier protection below it, but this will be partially counterbalanced by the saving in length. On the other hand, this does not imply that an abnormally wide site should not be selected when all the other conditions are satisfactory. It is always possible, if necessary, to restrict the width subsequently by means of training works. It is always difficult to foresee the effect of a weir on the silt deposits up stream, and while a long weir is more likely to cause irregular deposits than a short one, it by no means follows that this will be the case. The general principle is: to select a narrow site in preference to a wide one if other conditions are equal, but not to reject a wide site if it is the best on other grounds.

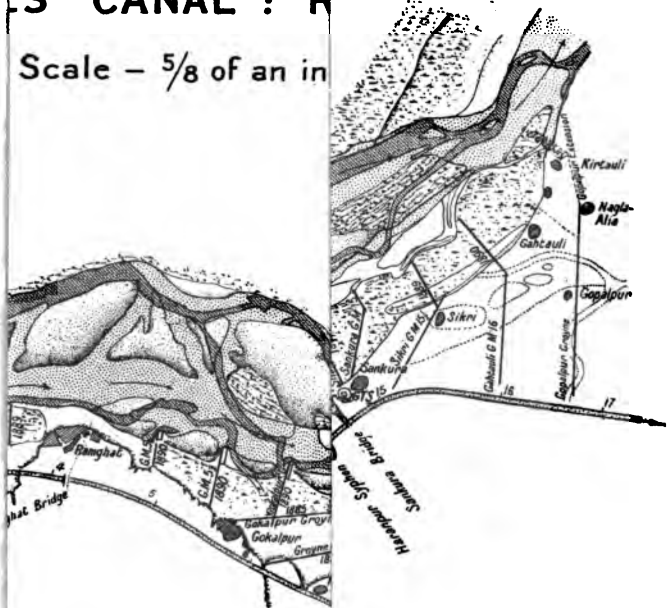
The arrangement of the Narora head works and training works is shown in Plate VI.

In the Indian types of submergible weirs it is necessary to

Plate VI.

S CANAL : R

Scale – 5/8 of an in



have arrangements for keeping the up-stream bed free of silt, or at any rate to keep open a clear channel leading to the canal head, so that the low-water supply may be diverted into the canal; and this is especially necessary when the weir is not provided with falling shutters on the crest.

For this purpose powerful scouring sluices are provided at the end of the weir, above which the canal head is situated. These sluices are generally called "under sluices," which is rather meaningless, and the term "scouring sluices" more properly defines their function.

The floor of the scouring sluices is placed at or about the level of the bed of the deepest channel of the river at the site of the works, and the general design is much the same as that of a barrage. There is a strong impervious floor, with a heavy talus to prevent cutting back, and the whole of the foundation is well packed in with puddle protected by heavy pitching. Above the floor the superstructure consists of piers with vertical grooves, in which are shutters of various types, manipulated from the top of the roadway by crab winches, so as to control the discharge through the vents.

At Narora the river above the weir is trained by groynes on both banks into a channel 3,000 feet wide, and for 4 miles has a practically straight run on to the weir. The weir itself is 3,800 feet long, and on the right flank are forty-two scouring sluices, divided by abutment piers into three groups of fourteen each, the vents being each 7 feet 3 inches wide. The total width of weir and sluices is 4,250 feet from abutment to abutment. The length of the weir and the width of the up-stream channel were fixed from data of the flood discharge of the river, and the highest flood then on record was taken as the basis of calculation. In consequence, the channel above weir is comparatively easy to control in high floods, but gives some trouble to prevent irregular silting in normal floods. There is no doubt that were the weir to be designed nowadays, the experience of the last thirty years would lead to its length being shortened by 500 feet. However, the channel difficulty has never become so acute as to necessitate the shortening of the weir, and the engineers who have had most experience of the works have been content to leave well alone.

The maximum flood on record occurred in 1880, when the depth on the weir crest was 7·35 feet. To the present-day engineer it is strange to read in his predecessor's flood report of 1880:—

"I very much regret to say it was impossible to get a river discharge of this flood. *It came down on us quite unexpectedly.*"

That was before the days of canal telegraphs, and nowadays the engineer with the telegraph at his elbow would be receiving hourly reports of the up-stream gauges twenty-four hours at least before the flood was due. Although no discharge observations were taken, the author has calculated the discharge from the records of river levels, and it amounts to 230,000 cusecs, of which 48,000 were passing through the scouring sluices. The sluices were designed to take one-fifth of the flood discharge of the river, which agrees very well with these calculations. Notwithstanding the provision of these powerful sluices, it cannot be said that they are entirely successful in ordinary floods in keeping a deep channel open, but they are very effective in clearing away the silt after the floods, when the water is not so heavily silt-laden.

The floods of 1900 are typical as illustrating how scouring sluices fail to fulfil their function in floods, but become efficient once the season of high flood is over. For two-and-a-half months (July 1 to September 15) there were no excessive fluctuations of level at the weir; the average depth of water on the weir crest during that period was 3 feet, the minimum depth being 2·9 feet, and the maximum 4·4 feet, which gave a discharge of 115,000 cusecs. The floods were lower than the normal, but of uniform magnitude for a long period. For about two months there was a fight between the draw of the under sluices and a persistent bank of silt in front of the canal head, which masked about one-third of the canal sluices furthest away from the scouring sluices. By the middle of September this silt deposit was about 10 feet thick, and then the river began to fall and the draw of the sluices began to tell. In a fortnight half of the shoal was cut away, and the river got so low that by raising the falling shutters on the weir a powerful current was forced through the scouring sluices, which cut away

the remainder of the shoal, leaving a perfectly clear channel for several hundred yards up stream.

The final result of the scouring operations in 1900 was that the river channel was in a more favourable condition for maintaining a supply in the canal than had ever been known previously, and was noted by the Chief Engineer as the standard condition to be aimed at in the regulation of the river.

CHAPTER IV

THE DEVELOPMENT OF IRRIGATION IN EGYPT SINCE 1884

THE prosperity of Egypt depends almost entirely on its irrigation, and though irrigation has been practised continuously for over 4,000 years, one has to go back but five and twenty years only to arrive at the first dawn of successful scientific irrigation in the valley and delta of the Nile. Up to the beginning of the nineteenth century, irrigation in Egypt, on a large scale, was practised only during the Nile floods. The whole valley in Upper Egypt was divided by earthen embankments into compartments varying from 2,000 to 60,000 acres in area, the banks standing well above the highest flood level. During low Nile, channels were cut in the river banks, and the lateral fall of the country being from the river outwards, the compartments were filled as the flood level rose with water heavily charged with fertilising silt. The water remained in the compartments for four or five weeks, depositing its silt and gradually receding as the river fell. When the alluvial deposit was sufficiently hard it was lightly scratched with the plough, barley, wheat, or other crops were sown, germinated, and came to maturity without any further watering. In Lower Egypt irrigation was effected from inundation canals, the water level depending on the height of the flood, there being no means of holding up a low supply by regulators or dams.

In 1805 Egypt fell under the vigorous rule of Mehemet Ali Pasha, who controlled the country for over forty years. He was quick to grasp the possibilities underlying Egyptian irrigation, and realised that, given a perennial instead of a flood supply in the canals, it would be possible for Egypt to produce, under favourable conditions, valuable crops of cotton and sugarcane for the supply of the European markets.

The Nile in flood rises about 25 feet at Cairo, and Mehemet Ali's first scheme was to deepen by 25 feet the canals existing

in the Delta so as to carry water during low Nile instead of during high Nile only, and thus secure a perennial supply. This enormous work was doomed to failure from its initiation. The existing canals had been dug with no attention to levels or grading, and after they were deepened they silted up during the next flood. The water level in the canals was dependent on the level in the river, and during the hottest months in the year, when the demand for irrigation was most intense, the supply in the canals failed and large areas of cotton perished.

The Pasha's next scheme was to raise the level of the low Nile sufficiently to supply the Delta irrigation, by building regulators across the Rosetta and Damietta branches of the river just below the apex of the Delta. This work was entrusted to Mougel Bey, a French engineer, and his designs resulted in the construction of the splendidly conceived Delta barrage, which, however, was a complete failure owing to causes presently to be described.

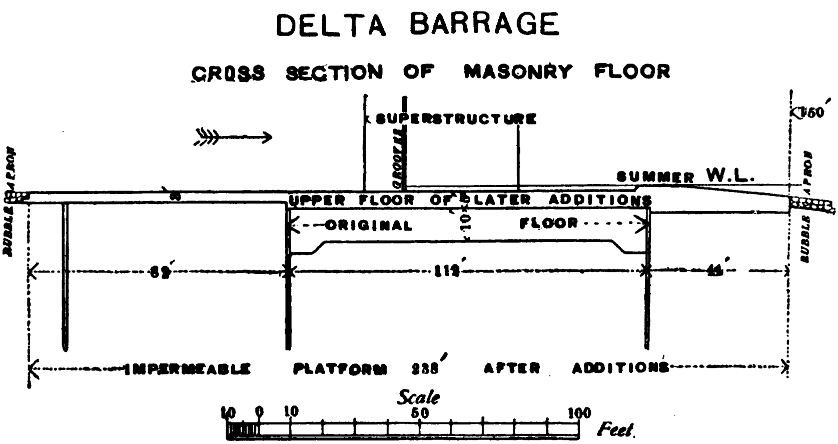
An integral part of the scheme was the construction of three canals—one to the west of the Rosetta branch, a second to the east of the Damietta branch, and the third to command the central portion of the Delta between the two branches. The central canal was completed and has done good service. The eastern canal was never begun until after the British occupation; and the western canal, though dug, was constantly silted up by drift sand from the desert. Year after year it was cleared out by *corvée*, or forced labour, but it was finally abandoned as a failure.

The Delta barrage consisted of two regulators, that on the eastern or Damietta branch having seventy-one arches, and the other on the Rosetta branch having sixty-one arches; each arch had a span of 5 metres or 16½ feet. The general design is shown on the diagram (Fig. 3). It consisted of an impermeable floor 10 feet thick, composed of concrete surfaced with ashlar, and the length of the floor was 112 feet to withstand a head of 14 feet. The piers were raised above high flood level, and were fitted with grooves for regulating gates, and carried arches supporting a roadway. The work was begun in 1843, and was completed in 1863 at a cost which can never be known, constructed as the work was by forced labour. In 1863 the gates

of the Rosetta branch were closed, but under a small head of water the work settled and cracked, and the gates were immediately thrown open. The experiment of closing the gates was repeated year after year till 1867, when the barrage cracked right across from top to bottom. The damaged portion was shut off by a coffer dam; and until 1884, when it came under the hands of the Indian engineers, the barrage was stamped as a hopeless failure.

Although the irrigation schemes of Mehemet Ali resulted in nothing but failure, it must be remembered that they contained the germ which, under expert treatment, developed into the

FIG. 3.



highly successful system of Delta irrigation of the present day. In justice to the memory of a great engineer, it must also be noted that as regards the design of the barrage there is nothing very much to cavil at. An impermeable floor 10 feet thick and 112 feet long to resist a head of 14 feet is a design which modern engineers would probably consider insufficient; but, given good workmanship, the barrage would most likely have been a success, although it might not have held up the whole head of 14 feet. The cause of the failure of the barrage may be given in a few words. Mehemet Ali was so impressed with the necessity of securing a perennial supply for the Delta canals, that he hurried on the work against the advice of his

engineers, and, overcome by his impetuosity, Mougel Bey's workmen laid the foundation concrete in running water. The cement was washed away, and the foundation of the work, instead of being an impermeable floor of concrete was nothing more than a mass of broken stone through which springs and pipes found an easy passage. As regards the length of the impermeable floor it may be noted that the designer of the Chenab weir, with the experience of fifty years to guide him, allowed a length of 108 feet against 112 feet allowed in the barrage, and for much the same head of water.

So far, this sketch of the Delta irrigation has been a record of failure; and we now come to the more pleasing part of its history, which begins with the arrival in 1884 of Colonel (now Sir Colin) Scott Moncrieff and his staff of Indian irrigation engineers.

In 1883 it was proposed to abandon the barrage altogether as an irrigation work, and to retain it simply as a bridge; and a scheme was prepared to irrigate the Delta by pumping water from the river. The pumping installation was estimated to cost £700,000, and the annual working expenses were to be £250,000. Before a decision regarding this scheme was arrived at, the management of Egyptian irrigation passed into the hands of Colonel Scott Moncrieff, who vetoed the pumping scheme and decided on the restoration of the barrage. To anticipate the sequence of events, it may be mentioned that the cost of restoring the barrage was £475,000, and an additional £500,000 were spent on the eastern and western canals. The annual cost of maintenance and regulation of the barrage is under £10,000, and is unaffected by any extension of irrigation. The annual cost of working the pumping scheme was estimated in 1883 at £250,000, and would moreover increase with the extension of the irrigated area, and be adversely affected by any rise in the price of coal, which is all sea-borne.

The restoration of the barrage was by no means viewed favourably by the engineering profession of the day, and the following passage occurs in a paper in the Proceedings of the Institution of Civil Engineers for 1884:—

"After the Sudan troubles . . . he (Col. Scott Moncrieff) unfortunately determined to make an attempt to raise the waters of the Nile by means of

the Barrage and that work is now being strengthened in a manner which he expects will enable it to perform the office for which it was designed. Most experienced engineers, native and foreign, believe that the attempt will end in failure. . . . Col. Scott Moncrieff and his assistant (now Sir William Willcocks) have been but a short time in the country; they have not yet seen the Nile through all its phases. It would surely have been more prudent to postpone the dangerous experiment of dealing with the Barrage to a future time."

It is fortunate for Egypt that, undeterred by adverse criticism, Colonel Scott Moncrieff persevered with the restoration work which finally was such a triumphant success, although its actual completion did not take place until after he had handed over the reins of office to Sir William Garstin.

The principle on which the restoration was based was the same as on the Narora and Khanki weirs, viz., to lengthen the impermeable floor. The width of floor was increased from 112 to 238 feet, two-thirds of the new floor being up stream. The original floor was also strengthened by a covering of 4 feet of Portland cement concrete, over which was placed a 15-inch layer of ashlar under the arches and where the action of the water was most severe (see diagram); and in some places where the floor was most seriously damaged the thickness of the new flooring was increased to 6½ feet. A line of sheet piling 16 feet deep was also driven along the up-stream face of the floor. After this work was completed, the barrage was found capable of holding up a considerable head of water, but springs appeared down stream of a certain length of floor. A shallow trench was dug up stream of the floor, where the sources of the springs were situated, and the springs were stopped by laying a clay apron under water, protected from scour by cement concrete laid in sacks. When this work was completed in 1890, the barrage was found capable of holding up a head of 13 feet of water.

The unsound state of the foundations was, however, a source of much anxiety to the engineers. In 1883, when the work was being examined with a view to converting it into a railway bridge, a diver was able to make his way right underneath and across the floor. It was therefore decided to strengthen the foundations by injecting into the cavities Portland cement grout, under pressure, on the system used by Mr. Kinipple on the rsey breakwater. Holes 5 inches in diameter were bored

through the piers from the top of the roadway to the bottom of the floor, a depth of 57 feet. Cement grout was then poured into the bore-holes, and the filling was continued until the grout reached the roadway level. The bore-holes were about 10 feet apart, and the pressure exerted by the column of liquid cement at the bottom of the floor was about 2½ tons on the square foot. This pressure was sufficient to force the cement into all the cavities below the floor, and to consolidate into one mass all the loose ballast in the foundations from which the cement had been washed away during Mougel Bey's original construction of the barrage. The details of this interesting method of strengthening the foundation will be found in a paper by Sir Hanbury Brown in Vol. LVIII. of the Minutes of Proceedings of the Institution of Civil Engineers. After this last operation, which was completed in 1898, the barrage was subjected to a head of 14 feet of water without showing any signs of undue strain.

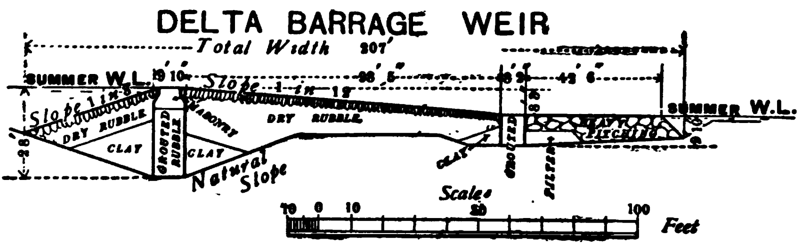
Although the barrage had now been rendered capable of holding up the head of water for which it was originally designed, something more remained to be done. It was felt that a work of such vital importance must be relieved of all possible strain, and, in addition, it was foreseen that the rapid extension of irrigation would require a greater head than 14 feet at the apex of the Delta. Subsidiary weirs were therefore constructed on the two branches of the river below the barrage, so as to hold back the water on the barrage floor and thus reduce the pressure. The work was begun in 1899 and completed in 1901. After the construction of the weirs the water level above the barrage could be raised to 20 feet above the floor, but the effective head on the barrage was reduced to 10 feet, the remaining 10 feet being supported by the subsidiary weirs. This arrangement secures a more perfect control over the distribution of water in the Delta, and has removed all misgiving as to the security of the barrage.

The design of the subsidiary weirs is based on that of the Dehri weir on the Sone, and is sufficiently explained by the diagram, Fig. 4. An interesting feature of the design is the inverted filter below the footing wall. It is composed of material gradually increasing in size, the lower stratum being

of small stone. The filter allows percolation water to pass freely, but prevents the passage of sand, and is a reproduction of an arrangement used with the same object on some of the Indian canals. The effect of the restoration of the barrage on the irrigation of the Delta has been an increase in the value of the cotton crop of Lower Egypt amounting, at a very low estimate, to more than five millions sterling per annum.

The restoration of the barrage was a work which had baffled the ingenuity of many successive engineers of all nationalities who were consulted by the Egyptian Government; and all credit must be given to Sir Colin Scott Moncrieff and his assistants for the solution of an exceptionally difficult problem.

Fig. 4.



We now come to consider the improvements in the inundation system of irrigation in Upper Egypt.

During the exceptionally low Nile floods of 1888, an area of 260,000 acres was left untouched by the rise of the river. The result was a loss of £300,000 of land revenue, and a very much greater loss to the cultivators of the whole of their crops. The attention of the irrigation engineers was thus forcibly directed to the improvement of the inundation system of irrigation. The improvements are largely due to Colonel Justin Ross, R.E., who was the first engineer in Upper India to place the alignment of minor irrigation channels on a scientific basis.

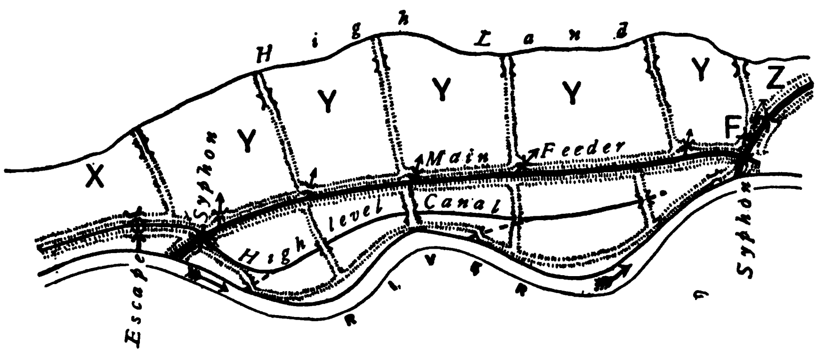
When the water surface of a river is higher than the adjoining fields, all that is necessary in order to flood the fields is to cut leading channels through the river banks. Owing to the deltaic nature of the Nile valley the lands close to the river are several feet higher than ordinary floods, and in a low flood most of the land close to the river is beyond the reach of the water. Short

canals were sufficient to flood the low-lying area, but the flooding of the high lands close to the river was a constant difficulty.

The slope of the Nile valley is about 6 inches a mile. If we suppose a canal taking out of the river and aligned with a slope of 2 inches a mile, then the water surface of the canal gains on the level of the ground at the rate of 4 inches a mile. If the ground surface at the head of the canal is 2 feet above the water surface, then after running 6 miles the water in the canal will be level with the ground. Nine miles further on, that is 15 miles from the head of the canal, the canal water surface will be 3 feet

FIG. 5.

IMPROVED BASIN SYSTEM



above the ground, and the canal is capable of flooding the country to a depth of 3 feet.

This is the principle which has been made use of in improving the basin system of irrigation of Upper Egypt. The high land near the river is divided off from the low-lying area by an embankment parallel to the river and the inundation of this high land is effected by a high-level canal which draws its supply from a point 15 or 20 miles higher up the river than the area which it inundates. The low-lying area is inundated by a short canal taking its supply from the river at a point sufficiently high to command its own area, and the tail of the high-level canal crosses the head of the low-level canal and is siphoned under it.

A complete basin system (see diagram, Fig. 5) thus requires two canals, 1st a low-level canal running parallel to the river and

delivering to each low-lying basin (Y) its fair share of muddy water, and 2nd a high-level canal, the tail of which is siphoned under the head of the low-level canal and supplying water to the high-level basins near the river bank which without this arrangement would receive no water during low floods.

The distribution of large volumes of water over a chain of basins necessitates the construction of a system of regulating works to secure complete control. These consist of head sluices to control the admission of water from the river into the canal, basin sluices to admit water from the canal into the basins, regulators in the cross banks of the basins to pass the water from one compartment into the other and to regulate the water level, and escapes to discharge the water back into the river.

The programme of operations in basin irrigation is somewhat as follows:—

On a fixed date (about the middle of August) the basin sluices are opened and the basins begin to fill. The escape channels are also opened and water flows into the basins connected with the escape channels; these escape channels are closed as soon as the water coming down from above causes a backward flow into the river. To ensure a good deposit of silt, the basin sluices are kept open after the basins are full, and the water level is regulated by means of the escapes, the average depth of water in the basins being kept at about 3 feet. By the end of September, all the basin area is under water and the emptying process begins about October 5. The supply from the river is cut off, and the water is passed forward from basin to basin until it is finally discharged through the escape channel into the river. In a fortnight or three weeks the basins are empty, the seed is sown broadcast and the crop takes care of itself until ready for harvest.

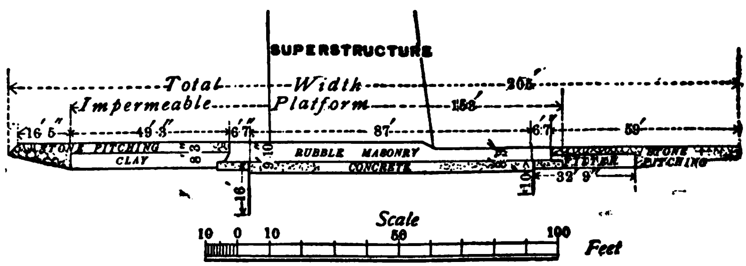
In the country served by the basin system of irrigation there was one exception to the general rule. The Khedive, Ismail Pasha, owned large estates round about Assiut, Lat. 27° N., and in the Fayum, between the twenty-seventh and twenty-ninth parallels of latitude; and in order to irrigate sugarcane in this district he constructed the Ibrahimieh Canal, which takes out of the Nile at Assiut and runs parallel to the river for about 200 miles, with a branch irrigating the Fayum. This canal was

intended to be a perennial canal, but as there was nothing to regulate the supply it was merely what is called in India an inundation canal, *i.e.*, a canal in which the supply fluctuates with the level of the water in the river. This canal was badly aligned, crossed most of the natural depressions of the country, and did much harm by its interference with natural drainage. Many of its defects were remedied, but in order to secure a perennial supply it was necessary to provide means for raising the water level when the river was low. This was effected by the construction of the Assiut barrage. This barrage is of

Fig. 6.

ZIFTA BARRAGE

CROSS SECTION OF FLOOR



the same type as the Delta barrage and has 111 spans of 5 metres.

Its length is about half a mile and it supports a head of 8 feet. The work was begun in 1898 and was finished in 1902. The ratio of impermeable floor to head is about 17 to 1, which is somewhat greater than the ratio in more recent designs.

After the restoration of the barrage the expansion of irrigation in the Delta necessitated the construction of a barrage across the Damietta branch of the Nile at Zifta. This work, begun in 1901, may be taken as the most approved design of the Egyptian type of river regulator. The construction details are shown in the cross section of the floor in the diagram (Fig. 6).

The following extract from Sir Hanbury Brown's "Irrigation" enumerates briefly the benefits which immediately followed the

establishment of an efficient system of control and distribution of the Nile waters:—

"The cotton crop, the modern source of Egypt's wealth, has increased from 3,000,000 to 6,000,000 cwt., or in value from £7,500,000 to £15,000,000; the maturing of the maize, the peasant's food crop, has been assured by its timely sowing being made a certainty; the cost of raising crops has been lessened by improved means of irrigating them; the cultivable area has been increased from 5,000,000 to 6,000,000 acres; the value of land has been more than doubled; and the system of forced and unpaid labour, with its attendant abuses, has been abolished. The capital expenditure which produced these results was about £4,000,000."

Intimately connected with the remodelling and improvement of the existing irrigation systems was the introduction of an efficient system of drainage. The evils which, in an irrigated country, inevitably follow any interference with the natural drainage outfalls, viz., waterlogging and the formation of saline deposits, necessitated some thirty years ago the realignment of practically the whole of the network of distributing channels of the Ganges Canal in India. Many of the channels were carried in embankments across natural depressions and there was either no provision or, at best, very inadequate provision for the passage of drainage. Large areas of land were thrown out of cultivation and the remodelling of the channels to run on the ridges of the country, together with the provision of drainage crossings, caused a very heavy addition to the capital cost of the canal.

In 1884 Egypt was in exactly the same condition as the Ganges Canal area—there were no drains, and for want of them much land had been ruined and still more was rapidly relapsing into barrenness. The design of a drainage system for the irrigated area in Egypt was fortunately simplified by the practical absence of rainfall, as in such a case the volume of water to be discharged is proportional to the area irrigated and to the volume of water supplied for irrigation.

For main drains serving a large area the discharge is practically constant and continuous, and the discharge of the drain was taken at one-third of the volume of water supplied for irrigation to the whole area. For small branch drains serving areas in which irrigation is intermittent a larger volume must be provided for; as though the *total* volume discharged during long

periods is constant, yet the total discharge is made up by alternate discharges of high and low volume, according as irrigation is or is not being carried on. For branch drains one-half of the maximum irrigation allowance of water per acre was provided for. The maximum discharge allowed for irrigation in Egypt is 25 cubic metres a day per acre commanded on main canals, and 36 cubic metres on distributing channels. The volume which the drains were designed to carry was therefore 8 cubic metres per day per acre commanded for main drains, and 18 cubic metres for small branch drains. Drains intermediate between the main and small branch drains were designed to carry 10, 12, or 15 cubic metres per day depending on their position in the drainage system. Based on these general principles hundreds of miles of drains have been constructed in Egypt and the waterlogging and deterioration of the land has not only been stopped, but the lands which were ruined are now being reclaimed and made fit for cultivation.

Up to 1902 the Egyptian engineers had been engaged in the improvement of existing methods of irrigation and in utilising the available supply; having completed their work, their attention was directed to the possibility of storing the surplus waters of the Nile which ran to waste during the flood season.

The advantages of storing the surplus Nile supply had been suggested to the engineers ever since their arrival in Egypt, but they contended that the finances of the country necessitated the utilisation and improvement of all existing irrigation works before embarking on costly works which, though desirable in themselves, would have swamped the funds at their disposal. As the financial resources of the country improved it was found possible to undertake the construction of a dam across the river and store surplus water to supplement the supply in the canals during low Nile, and thus convert flood irrigation into perennial irrigation. This cautious policy of making irrigation pay its way was undoubtedly sound, and after the improvement of the existing irrigation works was successfully completed the next great work undertaken in Egypt was a storage work, pure and simple—the Assuan dam.

In constructing a dam across a river to form a storage reservoir there is always the difficulty to be faced that, sooner or

later, deposits of silt will fill up the storage basin and seriously affect the available volume of water. In Spain the Val de Infierno dam, which is 115 feet high, has for many years been simply a waterfall, the reservoir having silted up to the crest of the dam. The necessity of preventing silt deposit has led to the design of an insubmergible dam pierced by numerous large sluices. The first example of this class of work was the Bhatgarh dam in India, constructed about 1892. The dam is 127 feet high and is provided with fifteen sluices, each of 8 feet by 4 feet section with their sills about 100 feet below the crest of the dam. The object of the sluices is to provide a low-level passage for the early floods which are heavily silt laden. During the later floods, which contain comparatively little silt, the sluices are closed and the water is impounded in the reservoir.

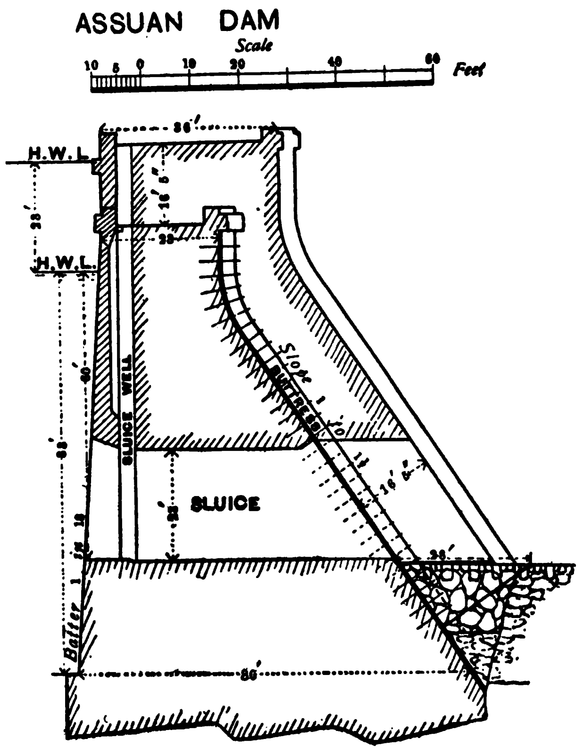
This principle of allowing the silt-laden flood waters to pass through the reservoir basin has been carried to its extreme limit at Assuan, which is the first insubmergible dam built without a waste weir to discharge surplus water. The total flood discharge of the river can be passed through sluices pierced in the body of the work and the possibility of the reservoir silting up is thus reduced to a minimum.

The site of the Assuan dam, a cross section of which is shown in Fig. 7, is at the head of the First Cataract, where the bed of the river is a dyke of syenite on which it was found possible to construct the dam without laying any foundations under water. The greatest height of the dam is 127 feet, and it impounds the waters of the Nile in a basin extending up stream for 140 miles, thus forming the greatest artificial reservoir in the world. The volume of the impounded water is roughly 40,000 millions of cubic feet. The dam is 1¼ miles long and it is pierced by 180 sluices each 6½ feet wide. These are placed at different levels to facilitate regulation and consist of forty sluices each 11½ feet high and 140 sluices each 23 feet high. A maximum flood of nearly 500,000 cusecs can be passed through the 140 large sluices with a heading up of about 11½ feet and a velocity of 21 feet a second. The maximum velocity through any sluice is nearly 35 feet per second.

Water heavily charged with silt and moving at these excessive velocities acts as a sand blast, and it has already been found

necessary to protect the down-stream toe of the dam from dangerous erosion. The river-bed below the work was originally left in its rough state, but this has now been levelled up by building an apron of masonry laid in cement so as to form a smooth talus down stream. The cost of the Assuan dam was £2,000,000, and its completion was a great advance in Egyptian

FIG. 7.



irrigation; but even the enormous storage it provided was very soon found insufficient for the requirements of the country, and the dam is now being raised by 23 feet. This work when completed will bring an additional million acres of land under perennial irrigation. Quite recently a dam of 120 openings of 5 metres each has been completed at Isna, 98 miles north of Assuan, at a cost of a million sterling. It will supply perennial irrigation to 180,000 acres.

The foregoing sketch of the development of Egyptian irrigation relates to projects which have been completed or which will shortly be completed. It remains to consider what yet has to be done, before Egypt receives the full possible benefit from her sources of supply.

The irrigable area of Egypt is now taken as seven million acres, and a volume of 12 cubic metres per acre per day is found to be sufficient for summer cultivation. The total daily discharge required for summer cultivation is therefore eighty-four million cubic metres. The ordinary available summer discharge of the Nile is about twenty-four million cubic metres, which allows for loss from evaporation in storage works, and sixty million cubic metres per diem have therefore to be provided by storing surplus water. The ordinary Nile supply has to be supplemented by storage for about three months, or, say, 100 days, so that the total storage volume required is 6,000 millions of cubic metres. The Assuan reservoir after the raising of the dam is completed will store some 2,500 millions of cubic metres, so that storage for 3,500 millions of cubic metres has still to be provided. Space does not permit of entering into a description of the action of the Nile tributaries in controlling its discharge, an interesting account of which is given in Sir William Garstin's lecture, "Fifty Years of Nile Exploration" (Geographical Journal, February, 1909).

On the Blue Nile, the Abyssinian branch, it is proposed to construct a regulating dam to supply a great canal which will irrigate three million acres in the Gezira province near Khartoum, though owing to sparseness of population and their ignorance of irrigation many years must elapse before this area is arrived at.

It is also proposed to control the torrential river Gash in the Eastern Sudan to supply irrigation in Kassala. These schemes, however, do not affect the problem of finding 3,500 millions of cubic metres of storage for Egypt proper.

Much of the waste on the Nile is due to the enormous evaporation and absorption in the great swamps, through which the river finds it way for 400 miles below Gondokoro. In this "Sudd" region, as it is called, from the masses of weed which block the flow of the river, the water spreads out laterally a distance of from 10 to 30 miles, and from actual measurement

it is found that from 50 to 75 per cent. of the supply coming down from the lakes is lost in the Sudd region. The summer discharge of the Nile at Lado above the Sudd is from 600 to 700 cubic metres per second, and 300 cubic metres only find an exit at the other end. The percentage of loss during a high flood is even greater than this; 2,000 cubic metres enter the Sudd and but 500 reappear.

It has been proposed, in order to minimise this enormous wastage, to construct an embanked channel from end to end of the Sudd region so that the side spill from the river may be controlled or prevented. This channel, if carried in a straight line through the swamps, would be something over 200 miles in length from Bor to Taufikia, the existing winding channel between these points being over 400 miles long. The prevention of waste in the Sudd would result in an addition of a daily volume of twenty-six million cubic metres to the summer discharge of the Nile, which is equivalent to a storage capacity of some 2,000 millions of cubic metres, allowing for unavoidable loss. This storage capacity, though an invaluable addition to Egypt's sources of supply for irrigation, is not sufficient to meet the existing deficiency, which is estimated at 3,500 millions of cubic metres, and further means of storage are therefore under investigation.

In addition to the raising of the Assuan dam and the construction of an embanked canal through the Sudd, there are three possible means of supplementing the supply in the Nile valley and delta.

These are: 1st, The construction of a dam, similar to the Assuan dam, in the river channel itself;

2nd, The construction of an artificial storage reservoir in the Fayum; and

3rd, The regulation of the discharge from the equatorial lakes, so as to store, for future use, water surplus to immediate requirements.

The success of the Assuan dam storage is a strong argument in favour of the first proposal; but the discovery of a suitable site is a difficulty, and it is practically certain that at Assuan the most favourable site has already been utilised, and any other must be of but subsidiary value.

The second proposal has great historical as well as engineering interest. The site of Lake Moeris is now generally accepted as covering the modern province of the Fayum. Moeris, according to Herodotus, was an artificial storage reservoir, and was used for storing the surplus Nile waters for use in the Delta during low Nile. The Wadi Rayan in the Fayum is a favourable site for a storage reservoir similar to Lake Moeris, but on a smaller scale. Its position some 60 miles above Cairo is suitable for the development of irrigation in the Delta which, however, is already sufficiently provided for by the restoration of the barrage.

The final proposal, viz., the regulation of the discharge from the equatorial lakes is the one which seems to be most promising, taken in conjunction, as it must be, with the construction of a channel through the Sudd. Sir Hanbury Brown has shown how the regulation of the discharge from the Albert Nyanza necessitates raising its water surface some 3 feet only, resulting in a storage of its supply for four months and a distribution of its stored waters during the remaining eight months of low supply.

Sir William Garstin has pointed out that much further information and study are still necessary before a final decision regarding Egypt's requirements is arrived at. The problem is difficult, but no engineer who has studied the development of Egyptian irrigation has any doubt that a solution will shortly be found, and that in the future, as in the past, Egypt's irrigation requirements will be provided for by the genius of Egypt's irrigation engineers.

CHAPTER V

ON THE DESIGN OF IRRIGATION CHANNELS

WHEN we consider that in India, speaking generally, less than 40 per cent. of the water entering the head of a canal does effective work in watering the fields, and that a considerable portion of this loss may be prevented by improvements in the design of channels, it is evident that there is room for much systematic research in this branch of canal engineering.

An irrigation system consists of channels to carry the water, of regulating works to control its flow, and of drainage works to carry surplus water from the irrigated area. The irrigation channels consist of canals, main and branch; distributaries, main, branch, and minor; and, finally, field watercourses.

For reasons to be explained presently, no direct irrigation is permitted from a main or branch canal in a modern irrigation system.

A canal, therefore, may be defined as a channel which carries water for irrigation, but from which direct irrigation on to the fields is not permitted. A main canal is one which directly taps the source of supply, and branch canals carry the water into different areas in the irrigated zone.

The term "distributary" is applied to those irrigating channels which distribute water to the fields and *are maintained by the State.* A distributary, therefore, is a Government channel or a whole system of Government channels, the supply to which is derived from a main or branch canal. The main line and principal branches are frequently called major distributaries whilst the smaller branches are termed "minors."

A *minor* may best be described as the last link in the chain of State distributary channels, taking off from a larger distributary (either main or branch) and delivering the *whole* of its supply into watercourses; whilst a *branch* may be defined as a channel intermediate between a main distributary and a minor, taking

off itself from a main distributary or from another branch, but with minors as well as watercourses taking off from it.

A watercourse is an irrigating channel which has a legal definition. It is defined by the Indian Act VIII. of 1873 as a distributing channel *which is not maintained at the cost of the State.* It may have been originally constructed at the cost of the State or under State supervision, and the State may even undertake its maintenance at the cost of the cultivators; but so long as the cost of maintenance is not borne by the State the channel is a "watercourse."

Attempts have been made to define main, branch, and minor channels according to their discharging capacities, and this practice has led to much confusion in irrigation terminology. It is well to have a precise definition of the names of the various irrigating channels, and that just quoted is due to Sir John Ottley, a former Inspector-General of Irrigation in India. The following remarks also are extracted from an unpublished paper written by the same authority:—

"In the present day an elaborate system of distributary channels for the conveyance of water from the parent canal to the villages to be irrigated forms an essential and important part of every new scheme for canal irrigation, the cost amounting to one-quarter, one-third, or even more of the cost of the supply channels themselves. So fully is the necessity for such expenditure now recognised that it is hard to realise that this has not always been the case and that in point of fact the system now so generally accepted as a matter of course, is really the result of exceedingly slow growth, nearly seventy years having elapsed since the first step was taken by Captain (afterwards Sir Proby) Cautley on the road which has since led by very gradual stages to the highly developed system of distributaries now obtaining on the most modern canals."

Sir John Ottley then goes on to show how the earlier canals had no distributing channels whatsoever, and how the waste of water which arose from the practice of allowing cultivators to carry water where they pleased, generally in channels aligned without any attention to levels or drainage, gradually forced the Indian Government to adopt the principle that all irrigation channels should be at least aligned by the State engineers, whether the construction and future maintenance were carried out by the State or by the cultivators.

The practice of permitting irrigation from the main canals

direct on to the neighbouring fields led to many abuses; the fields near the canal were over-irrigated, whilst those at a distance suffered; the unequal distribution of water was extravagant and led to loss of revenue, and in many cases the leakage along the primitive outlets in the canal banks caused serious breaches.

Without tracing in detail the development of the modern system of distribution, the present practice of delivering water on to the fields may be illustrated by quoting a note written in December, 1908, by Mr. C. W. Johnson, a Punjab irrigation officer:—

"Systems of 'watersheds' and 'valleys' obtain, not only among hills, but also in plains, which even if apparently flat, are made up of ridges and drainages more or less complex. The fundamental principle of irrigation engineering is to align the main canal on the main ridge with branches and distributaries on subsidiary ridges.

"Of late, owing to the extension of irrigation, the demand for water has exceeded the supply, and economy has followed mainly, perhaps, from the discovery that losses from evaporation and absorption are highest in the badly made watercourses leading from the distributary to the field, being 21 per cent. in the watercourses compared with 20 per cent. in the canal and 6 per cent. in the distributaries.

"Consequently it became recognised that the construction of these watercourses should not be left entirely to the cultivator, but that the watercourses should be aligned on the same principle as the larger channels. On the newer canals, the whole irrigated area is divided into squares of about 25 acres, with watercourses on the local ridges coinciding with the sides of the squares into which water is delivered from the highest corner.

"With regard to the longitudinal section of the channels the main desideratum is command, and in distributaries the Full Supply Level is designed about a foot above the ground surface when possible. Generally, however, a choice is necessary between several conflicting considerations, the next important after command being to avoid silting by giving the channel a silt-carrying capacity capable of carrying on all silt brought in by the water."

It will be observed from Mr. Johnson's note that 21 per cent. of the water entering the head of a canal is lost in the watercourses, and the design of small irrigating channels is therefore a matter of vital importance.

In designing the cross section of an irrigating channel we have certain data to consider. The statistics relating to areas suitable for irrigation have already been compiled, and the areas of irrigation to be effected in different villages, taken in

conjunction with the water duty, have determined the amount of water required for any given tract. The supply available may be less than the demand for irrigation, and the irrigable areas may have to be cut down to suit the available supply; but in any case the discharge allotted to the various irrigating channels is known. The longitudinal sections of the alignment of the channels, taken in conjunction with the fact that the water surface should be, if possible, about a foot above ground surface, fixes the possible surface slopes of the channels. We have therefore two factors more or less arbitrarily fixed, viz., the discharge of the channel and its surface slope. We have next to consider the variable or undetermined factors, viz., the bed width, depth of water, and the resulting mean velocity. Given the discharge and surface slope, there are many possible combinations of bed width and depth which might be selected, and in practice these dimensions are selected from tables of discharge for open channels, based on well-known formulæ. It is this combination of bed width and depth, together with the resulting mean velocity, which forms the more important portion of this lecture.

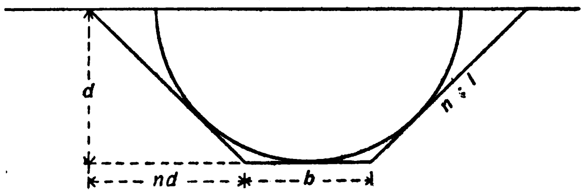
In the earlier days of irrigation engineering the design of channels was governed by the theorem of Neville, which lays down the conditions for the most economical form of channel, or, in other words, it lays down the dimensions which will give the section requiring the minimum amount of excavation for given side slopes and depth of water. Professor Unwin has shown that for a given discharge and given side slopes, the channel in which excavation is a minimum is that in which the hydraulic radius is one-half of the depth. As a corollary to this theorem it follows that when the hydraulic radius is equal to half the depth, then the bed and side slopes are tangent to a semi-circle described on a line representing the water surface and with a radius equal to the depth. This theoretical section is shown on the diagram (Fig. 8). It will be observed from the diagram that the channel of minimum section may be described generally as narrow and deep.

In large canals it is found in practice that the ratio of bed width to depth is governed by practical considerations rather than by theory. A deep channel is costly both to excavate and

to maintain, and, in addition, spring level would most probably be reached before the theoretical depth was attained. Excavation below spring level is very expensive, and in large channels, therefore, the practice is to make the depth of the canal as great as the local conditions will permit, and the bed width is then fixed so as to give the required discharge.

In all irrigation channels the question of silt deposit is very important. The amount of silt deposited in a canal should obviously be a minimum, and yet it is advantageous to take the light fertilising silt into the canal and to exclude the heavy sterile sand. The lighter silt acts as a fertilizer if carried on to the fields, or if deposited in the canal it helps to reduce percolation, acting as a self-deposited layer of puddle. A high

FIG. 8.—CHANNEL OF MINIMUM SECTION.



$$R=\frac{A}{WP} \qquad \left.\begin{array}{l} A=(b+nd)d \\ WP=b+2d\sqrt{n^2+1} \end{array}\right\} \text{min. when } R=\frac{d}{2}$$

velocity will carry silt forward, but a high velocity generally means a steep gradient and consequent loss of command, and too high a velocity will result in the scouring out of the bed.

The subject of the silt-carrying power of water as affected by the cross section of the channel has been very little discussed in professional literature. Mr. Flynn, in his book on "Irrigation Canals," mentions that the erosive power of water or its power of overcoming cohesion varies as the square of the velocity of the current, while the silt-transporting power of the current varies as the sixth power of the velocity. The resistance to be overcome in the one case is cohesion, and in the other case weight. If this conclusion be correct as regards the silt-transporting power of water, it is interesting as being, it is believed, the only known case in which the sixth power of a variable occurs in nature.

In large canals the successful management of silt deposit depends on practical experience rather than theory, and each particular problem has to be solved by methods adapted to local conditions. A concrete example will serve to illustrate how silt deposit is dealt with practically in large canals. In the early days of canal management a common practice was to increase the discharge in a canal during heavy floods on the assumption that with an increased mean velocity the stream would carry off more than the excess of silt thus brought into the canal. The excess volume of water was run off the canal by means of escapes situated some distance down stream. The experience gained by the regulation of supply on the Sirhind Canal in the Punjab, where silt deposit caused much anxiety to the engineers, has shown that this idea is entirely fallacious. On the Sirhind Canal the canal officer has to decide whether, for the purpose of keeping the silt deposit at a minimum, he should pass into the canal a supply greatly in excess of irrigation requirements, running the surplus out of the canal by means of escapes; or whether he should admit only the minimum supply necessary for irrigation. Briefly, the practice based on experience is to run as large supplies as possible when the water is lightly charged with silt, and to run minimum supplies only when the water is heavily silt-laden.

The practical question of the depth of supply which will cause a minimum of silting depends in most cases on the percentage of silt carried by the water. If the turbidity of the water is such that silt is deposited at a mean velocity of 2 feet a second, while the silt is all carried on by a velocity of 2·5 feet a second, it is evident that the depth of supply should be increased till a mean velocity of 2·5 feet per second or more is arrived at. On the other hand, if the turbidity of the water is such that no attainable mean velocity will prevent silt deposit, then the lower the supply, the less will be the volume of silt admitted into and deposited in the canal. The practical question as to the degree of turbidity at which it is desirable to stop flushing and run only minimum supplies is one that must be decided by experience for any particular case in which it arises.

On all modern canals a simple method of regulation is adopted which gets rid of much of the trouble formerly caused by silt

deposit. The head regulators are made very broad, and a thin film of surface water only is admitted into the canal. The surface water contains light fertilising silt only, and its admission into the canal is an advantage. The heavy sterile sand sinks below the level of the sill of the head sluices and is thus little drawn upon. This simple device has resulted in reducing much unprofitable expenditure formerly incurred in clearing silt deposit from the canal bed. From the foregoing remarks it will be seen that on large canals the design of their cross section and the selection of a mean velocity sufficient to minimise silting are both governed by practical rather than by theoretical considerations.

On small distributing channels the principles of design as governed by theoretical considerations can be adhered to more closely, and on these small channels the silt question becomes more acute than on large canals.

In a distributary 10 feet wide with a slope 1 in 10,000 a 4-foot depth of water gives a discharge of 53 cusecs. If silt to a depth of 6 inches is deposited in the channel, the discharge becomes 42 cusecs, or a reduction of 20 per cent. In a canal with the same slope, a bed width of 200 feet and 8 feet depth of water, a silt deposit of 6 inches causes a reduction in the supply of 10 per cent. only; and this silt deposit can generally be scoured out by flushing when the water is clear, whereas in the distributary the silt has to be dug out at a considerable cost.

The earlier Indian distributaries had many faults, and it is interesting to compare the principles of design in force at the present day with those generally accepted some forty-five years ago. Sir John Ottley, in the note already quoted, gives extracts from an article on irrigation published in 1863 by General Medley, and it is curious to note how nearly every principle relating to the design of distributaries laid down in 1863 by an expert is diametrically opposed to modern practice.

In the following paragraphs General Medley's principles are first quoted, and immediately following each the modern practice is noted:—

(1) The bed of a distributary will generally be from 1 to 3 feet higher than the bed of the main canal, and the distributary head takes out at this level.

In modern practice the bed level depends on the ground level; and in any case the sill over which water is drawn into the distributary is kept high and broad, so that only a thin film of the top water is drawn upon.

(2) Distributary heads were of two fixed spans, 3 feet and 6 feet. They are now made of any width necessary to give the required discharge.

(3) The heads of distributaries were kept deep, as otherwise fluctuations in the water level in the canal might interfere with the supply. A regulator is now generally provided in the canal below the distributary head, so that water may be held up as required.

(4) The slope should be as great as possible so long as the bed is not cut away by the induced velocity; 2 feet a mile is not too much, and below 1 foot a mile great inconvenience is experienced from silt deposit.

These heavy slopes were given to carry forward the silt drawn in from the canal by the deep-seated heads, and also to conform as closely as possible to the slope of the country.

In modern practice the slope is very seldom more than 1 foot a mile, and 0·56 of a foot per mile is of very common occurrence. This flat slope has two distinct advantages. First, the heavy silt is not drawn into the distributary because top water only is drawn upon. Secondly, the flat slope gives greater command, and when the bed gets too high above the country it is dropped down by means of a masonry fall. Falls were avoided in old channels because they necessitated a masonry work and added what after all was a mere bagatelle to the cost of the channel. The expense of clearing out the silt in an irrigation channel would cover the cost of many masonry falls.

(5) The practice of raising water to the level of the country by means of stop dams or planks introduced into grooves cannot be too strongly condemned; it converts what should be a running channel into a series of stagnant and unwholesome pools.

This is correct to a certain extent, but the remedy is to flatten the slope, and so gain command without using stop dams.

(6) When "*tatils*" are necessary they should be effected by

closing off outlets, and not by closing off distributary heads; keeping a constant supply in a distributary checks the growth of weeds.

"Tatil" means "closure," and is a method of distributing the water from a canal which runs constantly to areas which require water intermittently. Suppose, in a given area of crop, irrigation is required for five days consecutively and then no more watering is required for ten days. A distributing channel running continuously can irrigate a certain area for five days. That area then requires no more water for ten days, and the supply is delivered to a second area for five days, and again to a third area for the next five days. By means of this rotation a channel carrying a constant supply can irrigate for five days at a time three separate areas of irrigation each requiring irrigation for five days. When one area has received its five days' watering its outlets are closed off or "tatiled" and the water is passed on to the next area.

In former practice a channel, say, 15 miles long, was constructed: the first 5 miles received water for five days and the outlets were then closed; for the next five days the second 5 miles of the channel received water; and for the third five days the last 5 miles of the channel got water. The distributing channel, therefore, ran constantly for fifteen days and irrigated three 5-mile lengths in the fifteen days.

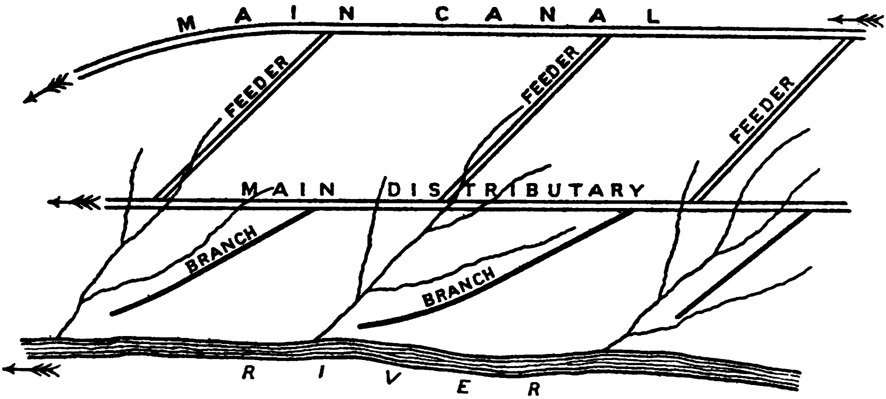
In the old system the channels carried silty water, and it was an advantage to run them constantly because weeds are killed by silt. In the modern practice comparatively clear water is run in the channels, and it is therefore an advantage to kill the weeds by shutting off the whole supply of a channel. In addition, the closure of portions of a channel gave unlimited facilities for peculation by subordinate officials; and experience has shown that to close off the whole of a channel is more efficacious than to keep it running constantly and close off portions only. In modern practice, therefore, instead of one long channel divided into three portions, each irrigating for five days, there would be three separate minors, and each of these would be shut off for ten days after performing its five days' irrigation. The introduction of a system of minors has resulted in the abolition of the "tatil" system, and is

characterised by Sir John Ottley as one of the greatest improvements ever made in canal administration.

(7) Once a year the bottom and side slopes of the channel should be cut away to the proper section. The "proper" section had 1 to 1 side slopes. Acting on this principle, large sums of money were spent annually in clearing silt from the channels and in cutting away the natural puddle which had been deposited on the side slopes and which has such an important effect in reducing percolation. Some thirty years elapsed before canal engineers recognised that heavy silt deposits could be prevented by improving the design of a channel, and that the self-assumed side slope of a channel in permanent *régime* was the one which should be maintained rather than an arbitrary slope of 1 to 1.

FIG. 9.

DISTRIBUTARIES.
Original System on Ganges Canal.



(8 and lastly) The general arrangement of distributaries was to have a main distributary running parallel to the main canal and midway between the main canal and the main drainage of the country. This was supplied by feeders run straight from the canal to the main distributary. The diagram (Fig. 9) shows how under this arrangement the irrigating channels were deliberately run across the drainage lines of the country. Drainage crossings were but little thought of, and the result

was serious flooding of crops and innumerable breaches in distributary banks.

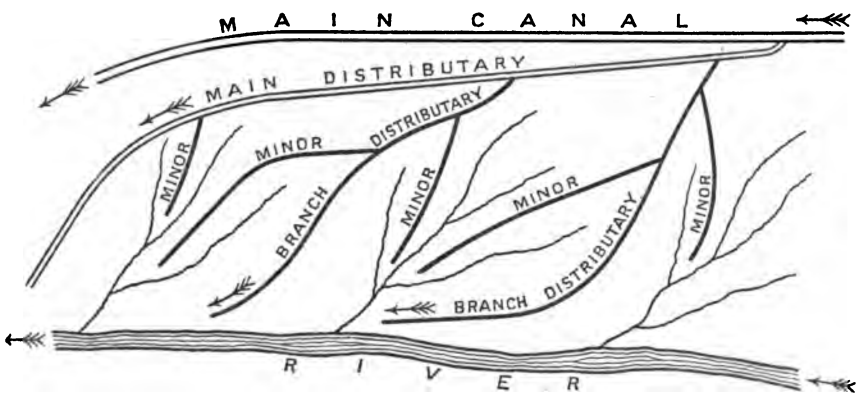
The second diagram (Fig. 10), which shows the alignment of distributing channels which would be adopted at the present day, sufficiently illustrates the difference between the two systems.

Enough has been said to show how the modern system conflicts with its predecessor, and some further points in the design of distributary channels will now be considered.

As a rule, distributary channels are excavated with side slopes of 1 to 1, as most ordinary soils will stand at that angle.

Fig. 10.

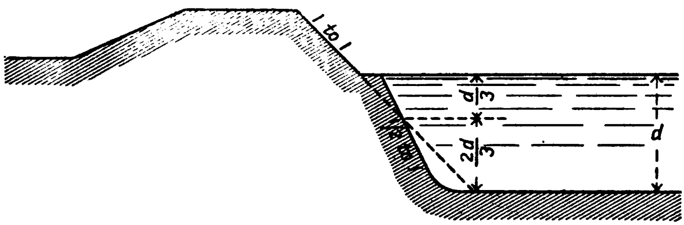
DISTRIBUTARIES.
(Modern System.)



This, however, is not the natural section which a channel will assume if left to itself. The natural side slope of a self-graded channel almost invariably approximates to ½ to 1; and this natural slope should never be interfered with, as it is the slope at which the self-deposited layer of puddle lies on the wetted perimeter of the channel. In designing the channel, therefore, the calculation of dimensions must be based on this ½ to 1 slope, although for convenience in construction the channel is excavated at a 1 to 1 slope. The relation between the bed width for a ½ to 1 slope as compared with a 1 to 1 slope can easily be got by drawing a section to scale of the dimensions indicated on the diagram (Fig. 11).

The ideal velocity in a distributary is that which will neither cause scour nor deposit silt, and this ideal velocity must vary with the character of the silt and with the nature of the soil. Mr. R. G. Kennedy's experiments on channels where permanent *régime* has been attained go to show that this ideal velocity is some function of the depth. The critical velocity at which silt begins to be deposited he expresses by the empirical equation $V_o = cd^m$, and for the particular channels on which he was experimenting $V_o = 0{\cdot}84d^{0{\cdot}64}$. It follows, therefore, that, within certain limits, a broad and shallow channel will be kept free from silt by a less velocity than a narrow and deep one—in other words, the broad shallow channel is less likely to silt. Everyone

FIG. 11.—SELF-SILTED CHANNEL.



will probably agree that the greater the mean velocity of a channel, the greater is its silt-carrying capacity, other things being equal. It is not so obvious that this capacity decreases with an increase of depth, and most engineers would be inclined at first sight to say exactly the opposite. It has been urged in opposition to Mr. Kennedy's theory that in most channels which occur in practice the greater the ratio of depth to bed width, the greater is the mean velocity, and therefore the greater is the silt-carrying power, and therefore the channel is less likely to silt. This sounds plausible, but in reality it begs the whole question at issue. It may be conceded that the greater the ratio of depth to bed width, the greater is the mean velocity; but Mr. Kennedy's contention is that the greater the ratio, the greater is the mean velocity required to prevent silting, and that in many cases, therefore, the advantage of increased velocity is more than neutralised by the disadvantage of increased depth.

As previously mentioned, the design of large canals depends more on practical than on theoretical principles, and it is therefore in the design of small channels that Mr. Kennedy's theory, if accepted, would be of importance. It is, moreover, in these small minors and watercourses that silt deposit gives the greatest trouble.

In one of the Punjab irrigation branch professional papers, Sir Thomas Higham has made a critical examination of the ratio of bed width to depth as affecting the discharge of small irrigation channels, and his results are exhibited in the following table:—

Ratio of bed width to depth	Hydraulic mean depth varies as	Mean velocity varies as	Absolute loss by absorption varies as	
0·33	0·355	0·428	2·091	
0·5	0·366	0·439	1·991	
1·0	0·378	0·450	1·838	
1·236	0·379	0·451	1·803	Maximum mean velocity.
1·5	0·378	0·450	1·789	
2·0	0·373	0·445	1·756	
2·5	0·366	0·438	1·751	Minimum loss by absorption.
3·0	0·357	0·428	1·755	
4·0	0·340	0·413	1·776	
5·0	0·324	0·397	1·807	
12·0	0·248	0·319	2·029	

He shows that with ½ to 1 side slopes the maximum hydraulic mean depth and velocity are obtained when the bed width is equal to 1·236 times the depth. Also that for values of the hydraulic mean depth lying between 1·0 and 5·0, and taking Kutter's coefficient of rugosity, $N = 0·025$, the mean velocity varies as $R^{0·82}$.

A minor watercourse designed with the bed width equal to 1·236 times the depth of water has a mean velocity which may be represented by 451, this being the maximum. Now minors are frequently designed with a bed width of 1 foot and 3 feet depth of water, the resulting velocity being as 428, or, say, 5 per cent. less. If, however, the minor were designed with a bed width of 4·4 feet and a depth of 1·46 feet (*i.e.*, a ratio of 3), then the resulting mean velocity is still as 428, and the channel has the

same area of cross section and therefore the same discharge as the narrow and deep channel.

As regards velocity only the broad and shallow channel is just as good as the narrow and deep one, and this without any reference to Mr. Kennedy's theory. If we accept Mr. Kennedy's theory, however, the shallow channel is very much better than the deep one, as the great reduction in depth reduces the velocity required to prevent silting.

The next point investigated by Sir Thomas Higham is the loss from absorption in shallow channels as compared with deep channels of the same capacity. Working on the Punjab formula for absorption,

$$\text{Loss in cusecs} = C\sqrt{d} \times \frac{W \, . \, L}{10^6},$$

he arrives at the proportional figures given in the fourth column of the table, and these are very remarkable.

The symbols in the formula are as follows:—

C = a coefficient usually taken as 3·5.
d = depth of supply in feet.
W = width of water surface in feet.
L = Length of any reach in feet.

It will be seen from the table that while the minimum rate of absorption obtains when the ratio of bed width to depth is 2·5 (2·472 gives the actual minimum), the rate of increase is much slower when the ratio is increased than when it is diminished. Thus when the ratio is increased to 5, the rate of absorption is less than when it is reduced to 1, and there is less absorption when the ratio is increased to 12 than when it is reduced to 0·33. From this it follows that, as regards absorption only, wide and shallow channels are better than narrow and deep ones, a result which seems surprising until it is realised how greatly the loss from absorption increases with the depth of the supply.

It must be remembered, however, that the channel of minimum *absolute* loss from absorption is not that in which the *percentage* of loss is a minimum. Absolute loss depends on the rate of percolation per unit of perimeter and is independent of the velocity. The percentage of loss varies directly with the absolute loss, and for channels of equal section it varies inversely with

the mean velocity. The ratio of bed width to depth which will give the minimum percentage of loss by absorption lies somewhere between that which gives the maximum velocity and that which gives the minimum absolute absorption. The ratio lies therefore between 1·236 and 2·472, or, say, that the ratio is 2 approximately. This would appear to be the ideal ratio as regards loss from absorption.

There is yet another form of wastage which must be considered, viz., loss from evaporation. The formula used in the Punjab canals for loss from evaporation is

$$\text{Loss} = \frac{2{\cdot}19 \times W \,.\, L}{10^6} \text{ cusecs.}$$

It will be seen that the loss for unit length varies directly with the surface width of the channel. It follows, therefore, that the narrower the channel, the less is the percentage of loss from evaporation. In distributary channels of ordinary sections the loss from evaporation is very much less than the loss from percolation, so that, considering mean velocity, percolation and evaporation, the general conclusion is that broad and shallow channels are better than those which are narrow and deep.

Apart from any theoretical considerations, a broad and shallow channel has certain advantages over a narrow and deep one.

(1) The less depth means a decrease in the height of the banks of the channel and a consequent saving in the cost of construction and maintenance. As a set-off against this, however, the wider channel occupies more land, which adds to the cost.

The second advantage is more important.

(2) The variation in water level due to variation in volume is not so great as in the narrower channel, and there is therefore a smaller loss of command over the land to be irrigated when the supply falls short.

The conclusion of the matter is that both theoretically and practically a broad and shallow channel is to be preferred to one which is narrow and deep—and this even if we reject Mr. Kennedy's theories; still more so if we accept them.

As regards the silting theory itself, it is difficult to conceive

that the transverse vortices which are induced in all channels in which the bed width has a finite value as compared with the depth should have no effect on the silting of a channel; and very possibly future investigations may show that bed width as well as depth comes into the empirical formula for the critical velocity. All that Mr. Kennedy claims for his theory is that in the absence of more extended experiments and data it may be regarded as a first approximation to the truth, and there is much room for future research in the direction where he has led the way.

As bearing on the silting theory it may be mentioned that for several years before Mr. Kennedy's paper was written it was noticed by canal officers on the old canals in the United Provinces that a channel in permanent *régime* in which there was neither scouring nor silting tended to assume a section much more broad and shallow than its original design; and this was specially the case in the field watercourses, which when once dug out were thereafter left very much to themselves. In the manual of professional instructions to irrigation officers the following appears under the head " Distributaries ":—

" To silt clear frequently the first 3 miles of a distributary is a confession of weakness, and remedial measures should be sought for. Silting at the head is due to one of the following causes:—

" (1) Excessive velocity in the parent stream, such as caused the silting in the Sone Canal;

"(2) Want of a raised sill at the head and insufficient opening;

" (3) Presence of tight siphons, bridges, or falls near the head of the channel; and

" (4) Want of sufficient width in the distributary."

Insufficient width, whether of masonry works or of channel, appears in three out of the four causes of silting, and this agrees with the conclusions already referred to.

Mr. Kennedy has published a series of graphic hydraulic diagrams which are much more easy to work with than the usual tables. They give in a graphic form discharges and mean velocities for varying bed widths, depths, and slopes, and are very useful in determining the dimensions of earthen channels

for given data; or, conversely, given the data, the tables may be used for determining the discharge. These diagrams can be used quite independently of the silting theory; they are simply graphs of the results got from working out Kutter's formula for discharge. A simple addition to the diagrams embodies the results of the acceptance of the silting theory. Curves representing the critical velocity are drawn across the diagrams, and the nearer the mean velocity approaches this curve of critical velocity, the better the section; in addition, curves are drawn representing the velocities at which scour may be expected in ordinary soils. These diagrams, though they include discharges up to 9,000 cusecs, are of most practical value in designing small channels.

To sum up the whole subject, Sir John Ottley has given in a very few words the guiding principles of the design of distributary channels:—

(1) Adherence to the ridges as far as possible.

(2) The conveyance of water to its ultimate destination by the shortest practicable route, in the largest volumes, in channels maintained in the highest possible state of efficiency and repair, and at such levels as will ensure rapid irrigation.

To these may be added that, other things being equal, a broad and shallow section should be selected in preference to one which is narrow and deep.

CHAPTER VI

IRRIGATION REVENUE AND LAND REVENUE IN INDIA

IT may seem strange that "Revenue" should be selected as the subject of one of a course of lectures on a specialised branch of engineering. The design, construction and maintenance of irrigation works come obviously within the province of the irrigation expert; it is not so evident that, as engineer, he is vitally interested in the control of the revenue derived from the works he has designed and constructed.

The Indian Irrigation Commission have dealt with the management of irrigation revenue as part of the duty of an irrigation engineer, and no apology is necessary for quoting largely from the report which they presented to the Houses of Parliament. To indicate the weight attached to the opinions of the Commission one need only mention that the engineer members were Sir Colin Scott-Moncrieff, to whom Egypt owes so much of her present prosperity, and Sir Thomas Higham, lately Inspector-General of Irrigation in India.

They write as follows:—

"We regard it of essential importance that the distribution of supply in all large irrigation works should be closely and continuously controlled by expert irrigation officers, who should be required to keep as strict an account of the disposition of every cubic foot of water entering their canals as they keep of the cash which they draw from the Government treasury. It is only by doing so that they can localise wasteful expenditure, or prevent an unequal or ineffective distribution of supply. The canal officer should also be regularly apprised of all applications for remission of revenue on account of flooding, or of the insufficiency or irregularity of the supply, in time to give him an opportunity of inquiring into the circumstances and taking the necessary measures to prevent their recurrence.

"We fully recognise the importance of placing large and important irrigation works under a separate staff of irrigation officers, who should not only as engineers be capable of designing, constructing and maintaining the works, but who should also be trained in revenue management, and devote all their energies to the improvement of the distribution and to the interests of the cultivator. We think that the more closely they are connected with the work of assessment and remissions, and with the settlement of all

questions connected with the internal distribution of water within the villages on which a reference is necessary to external authority, the more progressive and sympathetic will be the administration.

"It is, we are aware, sometimes contended that the engineer should confine himself to his own work, that of construction; and that the distribution of water, the settlement of disputes among irrigators, the assessment of water rates, and the disposal of claims for remissions are not properly an engineer's work at all, and would be better carried out by revenue officers and their subordinates whose training fits them for such questions of administration. We do not dispute that an officer who has been able to pass into the Indian Civil Service will be able to master the knowledge necessary to direct the distribution of canal water. But in the first place, his ordinary duties as a district officer leave him little time for such work, which must in practice be delegated to his subordinates; in the second, an officer who may have been able to devote his time and attention to the subject is very likely to be moved to another district where there are no canals, and to be succeeded by another who cannot interest himself in the matter; and in the third, the services of the engineer cannot be dispensed with altogether, for he will still be required to inspect frequently all channels and to attend to the maintenance of the works.

"If therefore a choice must be made between calling on the district officers to acquire the special knowledge required for the effective management of a large canal, or requiring the canal officers to learn the duties of a revenue officer to the extent that may be necessary for the purposes of canal administration, we should be disposed on these grounds alone, and for the sake of securing continuity in canal management, to prefer the latter alternative. But there is another reason to which we attach even greater importance. The successful manager of a large canal division, the *ideal* irrigation officer, should be something more than either engineer or revenue officer. He is constantly inspecting every part of the system, looking after both his public works subordinates on the canal works and banks and his revenue establishment in the fields and villages, and hearing all the petitions and complaints of the cultivators. Being thus in daily touch with the canal staff and the cultivators, he is always on the alert to propose improvements in the distribution of water and in all matters of management; his main concern being to get the most he can out of the available supply, not only by localising waste from Government channels or village watercourses, but also by constant adaptation of the distribution to the requirements of the moment or of the locality.

"It may well be doubted whether any of the improvements in distribution which have been made on the Northern Indian canals would have been proposed if the canal officers had been responsible only for the maintenance of the works. Under a dual control it would have been no one's business to initiate them" (Indian Irrigation Commission's Report, 1901-03, Part I., pp. 102, 103).

Nothing need be added to this explanation of the necessity of an irrigation engineer having a thorough knowledge of revenue administration.

Before describing Indian irrigation revenue systems it will be convenient to describe briefly, and in very general terms, the land revenue systems of India, as the two are intimately connected.

The right of the State to claim a share in a produce of the land has been a fundamental principle of Indian finance from time immemorial. We find it recognised not only under British administration and under the preceding native administrations, but also under what might be called the self-government of the early village communities. In early days the individual occupier of the land was not responsible for the revenue; the whole produce of the land held by the community was lumped together, and the community, represented by its headman, paid in kind a certain share of the produce to the ruler of the country.

This fundamental principle has been adhered to by the successive rulers of India, whether they be Hindu, Maratha, Moghul, or British; and the right to a share in the produce of the land is now, as it always has been, the most important source of the revenue of the State. In 1904-5 the land revenue amounted to 38 per cent. of the total net revenue of India, which was some eighty-five millions sterling.

In early times the share appears to have been one-sixth, which could be raised to one-quarter in time of need—during the progress of a war, for example. Just before the time of the Moghul emperors the share had gradually risen to one-half, and this was invariably paid in kind. Payment in kind still exists in India, but the land revenue, owing to the difficulty of assessment and collection, is now levied in cash, at least in British territory. The introduction of payment in cash instead of in kind was due to the emperor Akbar; but though the assessment was on a cash basis, it was at first left optional to the cultivator to pay in cash or in kind. The assessment was based on what is now called a cadastral, or revenue survey. The cultivable land was measured up and an estimate was made of the average yield of each kind of crop which might be expected from the land. The value of the produce was based on the average price of grain for the preceding nineteen years and the emperor's share was fixed at one-third of the estimated value.

This is the basis of the present-day procedure under British

administration, and the assessment of the amount of land revenue to be paid by a district is what is known as the "settlement" of the district.

With the decline of the Moghul empire the farming out of the land revenue became common, and there was little or no check on the demands of the revenue farmer, so that in most provinces the amount of land revenue collected was regulated by no fixed assessment and was limited only by the amount which could be wrung from the cultivator.

As British rule became paramount the assessments in the various provinces were investigated and the different systems were gradually reduced to order, but there was no attempt made to secure uniformity of system; the methods already existing were adhered to in so far as they were equitable, and thus it arises that the land revenue systems differ very considerably in different parts in India.

The various systems may, however, be roughly classified into two main divisions, depending on the status of the individual from whom Government demands payment of the land revenue. Where the revenue is demanded from the person or persons owning an estate the assessment is known as "zemindari"; and where it is demanded from the actual occupiers of the land or their representatives the assessment is known as "ryotwari." The zemindari system prevails in Northern and Central India and the ryotwari system prevails in Bombay, Madras, and also in Burma. Assam is also ryotwari. In British India 53 per cent. of the land revenue assessment is zemindari and 47 per cent. ryotwari.

The settlement of a district comprises two separate operations:—

(1) The preparation of the cadastral or revenue survey, which includes not only the preparation of the cadastral map, but also the preparation of a fiscal record, which shows the amount of the assessment and also the individual from which it is to be realised.

(2) The actual assessment of the land revenue.

The actual process of preparing the cadastral map need not be described in detail. It is simply a large scale survey, usually to a scale of $\frac{1}{4000}$, or about 16 inches to the mile, and is

drawn up sometimes by the staff of the Survey Department and sometimes by local surveyors, who base their work on traverses and triangulation carried out by the Survey Department. The work is very much the same as the preparation of the 25-inch map of the English ordnance survey.

A separate map is usually prepared for each "village," the Indian village being somewhat analogous to the English "parish." After the map is completed the fiscal register is prepared, the principal object of which is to enable Government to identify the persons who are responsible for payment of the land revenue. When the country was first acquired or annexed, it was found that various individuals had rights in the land. The cultivator was sometimes a temporary occupier; sometimes he had hereditary rights. In some cases he paid revenue direct to Government; in others he paid through an intermediary. The intermediary was sometimes the headman of the village, whose only concern with the land was the right to collect revenue; in other cases he was a revenue farmer appointed by the ruler; or in many cases he was a subordinate of the ruler to whom the revenue had been assigned as a reward for services rendered, the grant being often accompanied by the proviso that the grantee should keep up a military force for the service of the ruler in time of need.

In preparing the original fiscal record much investigation of ancient tenures was necessary, but gradually in each part of India a decision was arrived at as to the person who might be looked on as the proprietor of the land and who should be held responsible for payment of the land revenue. In the present day the initial record is carefully revised annually or at short intervals; alterations in land rights are recorded, so that when the assessments of a district are revised there is an up-to-date record of the individuals responsible for payment of the land revenue.

The next step in the settlement is the assessment of the revenue. The share of the State was originally a certain percentage of the gross produce of the land; but in the present day the share of the State is based on the net produce of the land, the cost of production being deducted. The value of the net produce is arrived at in various ways, which are too complicated

to treat of in detail. In general terms the assessment consists in dividing the areas into different classes of soils, the crops which may be grown on these soils are considered, the outturn from the various areas is determined, and a cash value for the outturn is based on certain accepted values for different kinds of produce. A liberal allowance is made for the cost of production, and the net value of the produce is taken as the basis, a certain percentage of which has to be paid to Government as land revenue.

The percentage of net land revenue demanded by the State varies in different provinces. In the older provinces the assessments are fixed for twenty or thirty years, and amount to some 50 per cent. of the net produce of the soil. In the newer provinces the assessments, being tentative, are revised more frequently, and the share of the State is generally lower than in the older provinces.

It is sometimes urged that in India direct taxation would be preferable to the imposition of land revenue. A discussion of fiscal policy is beyond the scope of these lectures, but it must be remembered that the payment to the State of a share of the produce of the land has been in force in India from time immemorial, and is therefore well understood by the people. A comparison between the incidence of the land revenue in the time of the Moghuls and in the present day may be of interest. The cash assessments of Akbar, according to contemporary records, represented one-third of the gross produce of the land; according to more recent authorities it represented one-quarter only. The Famine Commission of 1900-1 made certain calculations as to the incidence of the existing land revenue, and found that it varied from 4 per cent. in the Central Provinces to 20 per cent. in Gujrat of the gross produce, so that the demand of the British Government is very much less than the demand in the time of the most enlightened of the Moghul emperors.

Remembering the fundamental principle that the land revenue is the State's share of the produce of the land, and remembering also how irrigation increases the produce of the land, it is evident that irrigation revenue must be intimately connected with the land revenue.

In India the revenue from Government Irrigation Works is derived mainly from two sources:—

(1) From charges made for the sale of water;

(2) From charges made for "water advantage," which may be described as the benefit which accrues to the land by water being available for irrigation. In all cases these charges depend not on the actual volume of water supplied, which may vary largely according to the incidence of rainfall, but on the area actually or usually irrigated, and on the class of crop.

When the State's share of the land produce was taken in kind, the value of this share naturally increased with the introduction of irrigation. When the system of assessment of land revenue on a cash basis was introduced, the assessment of lands enjoying the advantage of irrigation was pitched higher than on similar land which had no irrigation. The difference between the assessment on irrigated or "wet" lands and on unirrigated or "dry" lands represented the revenue earned by the irrigation works.

In Madras the irrigation revenue is consolidated with the land revenue assessment. In that Presidency over 90 per cent. of the irrigated lands are under rice, and water is applied to the same fields year after year; and the system of lumping together the land revenue and the irrigation revenue has many advantages. The irrigated area is much the same year after year, and lands which can be irrigated have a higher assessment than those which get no water. The system is more elastic than that under which the cultivator pays a fixed rate per acre irrigated, the rate varying with the kind of crop. The settlement officer in fixing the land revenue in Madras takes into account not only the effect of irrigation in increasing the produce of the land, but he also takes into account the value of the increased produce to the cultivator. The produce of a field remote from a market is not so valuable as that of a field in close proximity to a market; and this is taken into account in fixing the land revenue, which includes the irrigation revenue. It will readily be understood; that the value of the produce of land close to a market may be increased by Rs. 20 per acre by the introduction of irrigation, while the cost of carriage of the produce of a field remote from a market would reduce the value of irrigation to Rs. 10 per acre.

In the consolidated system, therefore, the increase in land revenue assessment represents the State's share of the increased value to the cultivator of his irrigated produce; and this is in accordance with the usage from time immemorial.

The system of consolidated assessment is also followed on the older irrigation works in Bombay and in those districts in Burma which have come under settlement.

In Sind the principle is much the same, though the details are slightly different. There is practically no cultivation in Sind except by the aid of canal water. The land revenue is levied on the lands actually irrigated during the year, and nine-tenths of the land revenue assessed is credited to the canals as irrigation revenue. The land revenue is therefore practically a water rate varying with the area irrigated and the class of crop sown, although this water rate is assessed as land revenue. The system in Sind is very much the same as in Egypt. In that country payment of the land tax gives an absolute right to artificial irrigation; and the land which, from shortage of water or other cause, has not received water for irrigation is *ipso facto* entitled to remission of the land tax.

In Northern India the consolidation of land revenue and irrigation revenue is not possible. The irrigated fields are not the same year by year as in Southern India; much of the land irrigated in one year lies fallow the next; the demand is less constant and depends on the incidence of the rainfall; and in the rotation of crops the fields actually irrigated vary from year to year.

In Northern India and also in Bengal the charge for water is distinct from and independent of the land revenue assessment; it is levied as a water rate varying with the kind of crop, and is charged on the acreage actually irrigated. It is a charge on the user of the water, the tenant or the occupier, and is known as the occupier's rate. The application of water to land by the occupier results in an increase of the produce of the land, and the State therefore claims a share of this increased produce in accordance with the fundamental principle that the land revenue is the State's share of the actual produce of the land. This share of the increased produce is in fact land revenue, due to water advantage, and being land revenue it is levied not on

the user of the water, the occupier, but on the owner of the land.

When the land revenue has been fixed—that is, when the district has been "settled" for a term of years and after settlement irrigation is introduced—then the State's share of the increased produce is levied by the imposition on the owner of a rate on the area actually irrigated; and this is known as the owner's rate. In Upper India the owner's rate is one-third of the occupier's rate.

There are therefore three rates levied on the land when irrigation is introduced after settlement. These are: (1) the land revenue, which was estimated when there was no irrigation; (2) the occupier's rate, levied on the individual who uses the water; and (3) the owner's rate, an extra assessment of land revenue caused by the introduction of irrigation, and payable by the individual responsible for the land revenue, *i.e.*, the owner. The calculation and collection of these three rates means a considerable expenditure on revenue establishment, just as in this country the differentiation in the income tax levied on earned and unearned incomes has resulted in an increase in the cost of collection of the income tax. Two of these three sources of revenue are levied on the same individual, viz., the land revenue and the owner's rate, both payable by the owner of the land.

It obviously would reduce the cost of collection were these two taxes to be consolidated, and this is done when the current settlement expires and when a revision of the settlement becomes necessary. At revision of settlement the owner's rate is merged in the land revenue assessment, and in a re-settled district there are only two assessments: (1) the land revenue, payable by the owner and based on water advantage, *i.e.*, based on the fact that the lands can be irrigated; and (2) the occupier's rate, based on the class of crop and on the area actually irrigated by the occupier of the land. Under such conditions the revenue earned by a canal consists of the occupier's rate, a cash transaction; and of a certain percentage of the land revenue, a book transaction, which represents the difference between the land revenue which is actually levied and the land revenue which would have been levied had there been no irrigation. Owner's rate as an item of irrigation revenue is gradually disappearing as it

becomes merged into the land revenue, and in a few years the irrigation revenue in the Punjab and United Provinces will consist of occupier's rate and a certain share of the land revenue on lands having water advantage, being the difference between the land revenue on "dry" lands and on "wet" lands. In Bengal a permanent settlement was fixed under Lord Cornwallis in 1793; that is to say, the land revenue was fixed in perpetuity. This being so, the State cannot demand an increased land revenue although the produce of the land has been increased by the introduction of irrigation. The occupier pays the occupier's rate, and there can be no owner's rate because owner's rate is really an increased land revenue which cannot be levied. In Bengal, therefore, the landowner takes all the profits due to the increased rental which he charges on irrigated lands although the increase is directly due to the expenditure of capital not by the landowner, but by the Government, *i.e.*, by the general taxpayer. There is much to be said on both sides as to the advantages and disadvantages of permanent and periodical settlements. Against the permanent settlement, it may be said that the general taxpayer of India has provided funds for irrigation works in Bengal which have caused an enhancement of rentals; and the Government, which provided the capital, has no share in this enhancement—it is enjoyed by the Bengali landlord as a purely unearned increment.

On the other side it may be urged that, on the approach of a revision of settlement, lands are deliberately thrown out of cultivation in order to reduce the assets on which the land revenue assessment is based and so secure a reduction in the land revenue. Under a permanent settlement this is not the case, and the investment of capital in land is directly encouraged.

Without going into details, it may be said that permanent settlement in Bengal is not likely to be rescinded; and that from a purely irrigation point of view the loss of the "owner's rate" accounts mainly for the fact that, in Bengal, irrigation works are not directly remunerative.

As regards the actual charges for irrigation, these vary so much in different localities that it would serve no useful purpose to give them in detail. As a general rule they vary from 10 to

12 per cent. of the value of the crop, except in Bengal and the Bombay Deccan, where the average is about 6 per cent. of the value.

As pointed out by the Indian Irrigation Commission, there is one defect in all the existing systems of payment for irrigation in India. There is no direct inducement to the cultivator to economise water and to see that it is not wasted between the Government irrigation channel and the field. The payment for irrigation by volume of water actually used instead of by area actually irrigated is an ideal which has attracted most irrigation engineers.

In charging for irrigation by volume of water consumed, there are two systems which have to be considered: a charge by meter and a charge by module.

Under the meter system the cultivator would pay for the actual amount of water he uses for irrigation, the quantity being measured by a water meter. The system is precisely that in everyday use by gas or electric light companies. It is, however, altogether impracticable on a large irrigation system. The basis of the meter system is that the cultivator pays so much per unit for the water he uses. Any unit may be used. Suppose it to be 1 acre-inch or 3,630 cubic feet. In a rainy season two units of water may suffice for his crop, while in a dry season he may require ten units. In the latter case the cultivator pays five times as much as in the former, although the value of the crop remains the same. If the rate per unit be pitched very high, then in a very dry season the cultivator might have to pay more than his crop was worth, or in a wet year he might have to pay a comparatively small amount for a single watering, which nevertheless was absolutely necessary to save a valuable crop. It is practically impossible to fix an all-round meter rate for water which would meet all cases.

There is, however, a more serious objection to the meter system. On an extensive canal system the irrigation officer has to arrange for delivering a certain volume of water at a point which may be more than 200 miles away from the source of supply. When arrangements have been made for delivering water at a particular watercourse it ought to be paid for, whether the owners of the watercourse use the whole of it or not. A very large percentage of the water taken in at the head

of the canal in order to supply a watercourse is lost in transit, and when water has been passed down distributing channels it cannot be sent back again and utilised elsewhere. Under the meter system no charge is possible for water unless it is actually used, and for this reason the meter system is not suitable for large irrigation systems.

The function of a module is not to *measure* the quantity of water supplied, but to *control* it. A module gives a certain volume of water, and the action of the module keeps that volume constant, whatever may be the fluctuations of water level in the supply channel—this, of course, within certain limits. It is therefore possible to charge a rate for the module based on the supply which it discharges, whether the full discharge be utilised or not. The cultivator can lessen the discharge from the module, or he can shut it off altogether; he cannot increase the discharge. The difficulty lies in fixing a scale of charges which shall be equitable both to the Government and to the cultivator. Under the present system of charging by crop and by area irrigated the cultivator knows exactly where he stands; under the module system he undertakes to pay a certain contract rate for a certain supply of water which he may utilise as he pleases. The Indian cultivator is very conservative, and the introduction of a new system of charges for water supplied he looks on with suspicion. The module system of charging for water is, however, the only possible volumetric system on large irrigation works, and by cautious tentative experiments it may be possible to introduce a volumetric system of charges in India.

Contracts for a period of years for the supply of water for irrigation are entered into by the Indian cultivator, especially in Bengal; the module system of volumetric supply is essentially a contract, and there is therefore ground for hoping that when the Indian cultivator is educated to understand the module system, he will accept it to the great advantage of all concerned. It may be added that in countries where a volumetric charge for irrigation has been introduced—in Italy, in Spain, and in America—it is a module and not a meter system which is in force.

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